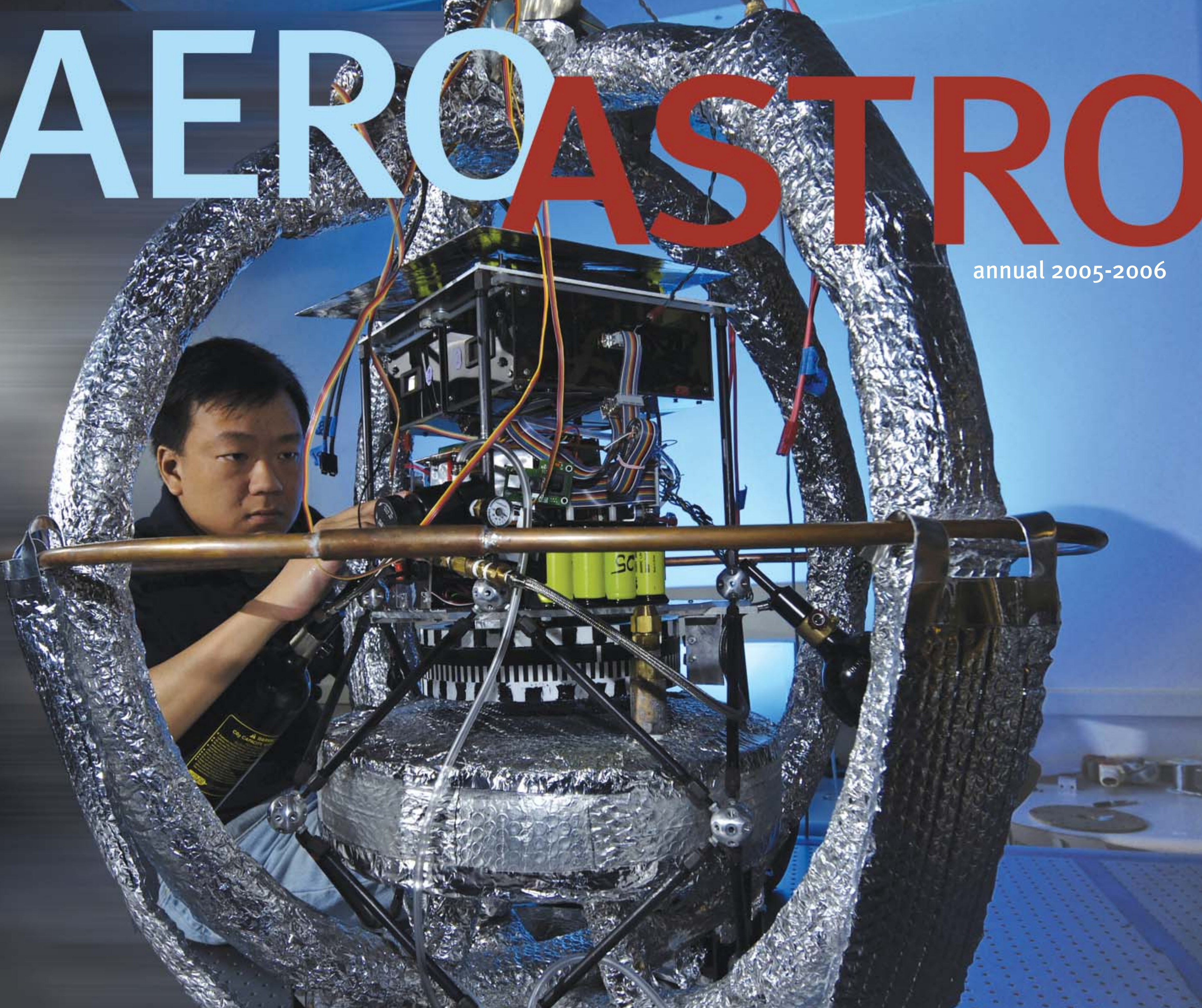
AERO ASTRO

annual 2005-2006



MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AERO-ASTRO

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DESIGN

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Cover: Research Scientist Edmund Kong works on an electromagnetic flight formation testbed in Aero-Astro's Space Systems Lab. EMF spacecraft flying in formation maintain positioning via electromagnetic attraction and repulsion. (Photograph ©Volker Steger / Science Photo Library)

Dear colleagues and friends:

Welcome to the 2006 issue of *Aero-Astro*. Featured in this issue are profiles of selected faculty and alumni, overviews of several of our many research areas, a focus article on undergraduate teaching of experimental and communication skills, and a spotlight on one of our many student driven initiatives. These articles feature what makes the Department so wonderful — the students, faculty, staff, and alumni of Course 16. Before you turn the page, we would like to add several other highlights from the headquarters perspective.

During the past three years, the excellence of our faculty has been recognized with many external honors. One of the highlights was this year's presentation of the Daniel Guggenheim Medal — one of the most prestigious honors in aerospace — to Professor Eugene Covert. A list of major awards presented to our faculty accompanies these comments.

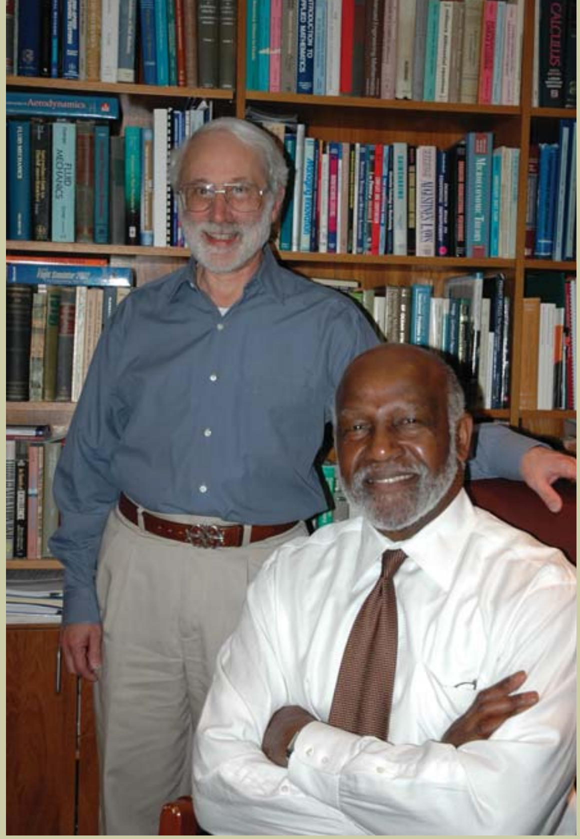
This year, the faculty paused to identify a set of Shared Values — principles and qualities to which we collectively aspire. They are:

- Excellence in our research, scholarship, and teaching
- Aerospace as a primary focus of our activities
- A commitment to faculty development, especially junior faculty
- Leadership through professional service
- Commitment to open research
- Mutual respect for our colleagues, and a collegial environment

We expect this to be a living list, to be periodically revisited and refined.

Looking towards the future, we are embarking on a complete review and revision of our graduate programs, including overall objectives, admissions, curriculum, pedagogy, and financial issues. The extent of this review, to be led by Professor David Darmofal, will take shape as this issue of Aero-Astro goes to press. We take pride in the past decade's reformulation of our undergraduate program with the Conceive, Design, Implement, Operate (CDIO) framework, and look forward to drawing upon that experience as we re-examine the graduate program.

To learn more about our Department, please visit our Web site http://www.mit.aero or, better yet, visit us at MIT.


Earll Murman (left) and Wesley Harris

Wesley Harris
Department Head

Earll Murman
Deputy Department Head

The Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, honors the profound awards and recognitions bestowed since 2003 on members of our faculty. Their collective stellar achievements are a gift to our department, to our Institute, and to our society.

We proudly acknowledge and thank the following individuals:

EUGENE E. COVERT
Guggenheim Medal, 2006

EDWARD F. CRAWLEY
NASA Public Service Medal, 2003
Fellow, Royal Aeronautical Society (U.K.), 2004
Fellow, Royal Swedish Academy of Engineering Science, 2005
Doctor of Technology, Honoris Causa, Chalmers University, 2006

MARY L. CUMMINGS
AIAA Distinguished Lecturer, 2004-2005

JOHN DUGUNDJI
AIAA Structures, Structural Dynamics & Materials Award, 2006

ALAN H. EPSTEIN
Gas Turbine Scholar, ASME IGTI, 2003
ISA, Maj. C. Bassett Outstanding Paper Award, 2005
ISA, Excellence In Documentation Award, 2005
Fellow, ASME, 2005

EDWARD M. GREITZER
ASME, R. Tom Sawyer Award, 2005

R. JOHN HANSMAN
Aviation Week and Space Technology Laurel, 2004
ATCA Kriske Career Award, 2005
AIAA Dryden Lecture in Aviation Research, 2005

WESLEY L. HARRIS
Doctor of Philosophy, Honoris Causa, University of Pretoria, 2006

DANIEL E. HASTINGS
NRO Distinguished Civilian Award, 2003
QEM Giant in Science Award, 2005

PAUL A. LAGACE
ICCM, Executive Council Honorary Member, 2003
Fellow, ASC, 2005

NANCY G. LEVESON
CRA N. A. Habermann Award, 2004
CRA Distinguished Professor, 2004
University of Illinois, UC, R. T. Chien Lecturer, 2004
ACM SIGSOFT Outstanding Research Award, 2004
NSB Presidential Mentoring Award, 2005
NSB Public Service Award, 2005
Harvey Mudd College Distinguished Lecturer, 2005

MANUEL MARTINEZ-SANCHEZ
ASME Melville Medal, 2003

EARLL M. MURMAN
IAA Engineering Book Award, 2003
Fellow, Royal Aeronautical Society, 2004
Foreign Member, RSAES, 2005

DAVA J. NEWMAN
AIAA Distinguished Lecturer, 2003-2004

DEBORAH J. NIGHTINGALE
IAA Engineering Book Award, 2003

AMEDEO R. ODONI
Fellow, Institute for Operations Research and Management Science, 2004
Doctor of Philisophy, Honoris Causa, Athens University of Economics and Business, 2006

JAIME PERAIRE
Fellow, IACM, 2004
Fellow, US ACM, 2005

NICHOLAS ROY
AIAA Distinguished Lecturer, 2004-2005

ZOLTAN S. SPAKOVSZKY
ASME Melville Medal, 2003

IAN A. WAITZ
Fellow, AIAA, 2006

MOE WIN
IEEE S. A. Schelkunoff Transactions Prize Paper Award, 2003
ONR Young Investigator Award, 2003
PECASE, 2004
Fulbright Foundation Senior Scholar Fellowship Award, 2004
Institute of Advanced Study Natural Sciences and Technology Fellowship, 2004
Fellow, IEEE, 2004
IEEE Distinguished Lecturer, 2005
IEEE E. E. Sumner Award, 2006

LAURENCE R. YOUNG
Fellow, Biomedical Engineering Society, 2005
Fellow, American Institute of Medical and Biological Engineering, 2005

CONTENTS

Aero-Astro Professor and former Shuttle astronaut Jeffrey Hoffman tests a Mars concept space suit at the Haughton Crater base on Devon Island in the Canadian Arctic during a 2005 visit by MIT researchers. The base offers some conditions similar to those that may be experienced on the Moon and Mars. (Jessica Marquez photograph)

Special delivery

MIT TACKLES INTERPLANETARY TRANSPORTATION OF SUPPLIES, EQUIPMENT, AND HUMANS

By Olivier L. de Weck

Between 1969 and 1972, Project Apollo achieved six lunar landings, enabling a total stay of 300 crew hours (12.5 days) on the lunar surface. Today, President Bush's Vision for Space Exploration charges NASA with a return to the Moon before 2020, and developing both lunar technologies and operational experiences as a springboard for human missions to Mars and beyond. The new challenge is how to accomplish this under a constrained budget and in a sustainable manner, using the Moon as a stepping stone to Mars. NASA is conducting studies, and has engaged industry and academia in this pursuit. Among academic institutions, MIT is playing a central research and educational role in the Vision for Space Exploration.

A number of large projects are underway at MIT, spearheaded by the Department of Aeronautics and Astronautics, to help the nation meet this challenge. The first of these was the Concept Evaluation & Refinement (CE&R) study, conducted jointly with the Charles Stark Draper Laboratory in 2005-2006. This involved a team of eight faculty members led by Professor Edward Crawley, and about 30 graduate students, mainly from Aero-Astro. The project gave us a first opportunity to specify what is required to achieve sustainability in space exploration: value delivery, affordability, risk/safety, and policy robustness. A focus on value delivery ensures that new discoveries are continuously generated and that public interest and a consistent level of funding are maintained over time. Affordability minimizes lifecycle costs, not just development costs, and upfront consideration of risk and safety helps avoid hazards from the start. Policy robustness ensures that the exploration program will survive changes in objectives, leadership and funding through a modular, step-like approach. As part of the CE&R study, we also developed specific recommendations for lunar transportation architectures, the design of the Crew Exploration Vehicle, and other mission elements.

COMMONALITY IN THE DESIGN OF PROPULSION SYSTEMS, LANDING GEARS, TANKAGE AND STRUCTURAL INTERFACES, AVIONICS, AND SOFTWARE WAS IDENTIFIED AS A HIGH PRIORITY.

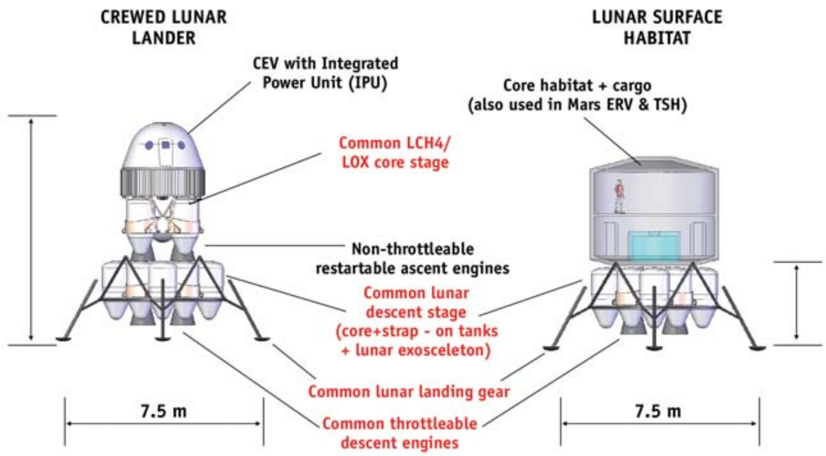
One of the keys to affordability is a high degree of commonality and modularity among mission elements. This is true even if some performance penalties and inefficiencies in individual elements are encountered along the way. Commonality in the design of propulsion systems, landing gears, tankage and structural interfaces, avionics, and software was identified as a high priority. We also developed methods and tools for quantifying both the benefits and penalties of commonality for sets of future exploration missions and elements with applicability to NASA and other industries. However, this requires a paradigm shift by decision makers to not evaluate space missions one-at-a-time, but to consider the effects over an entire program. The other key idea we developed is designing systems so that they are easily evolved over time and adaptable for new missions. We pioneered the "Mars-back" approach, where hardware is primarily designed for the long-term objective — Mars — and accommodations for lunar use are only made where absolutely necessary.

PARADIGM SHIFT: SPACE LOGISTICS

It is becoming clear that to be sustainable over the long term, a fundamental paradigm shift has to take place to include operational considerations early in the design of space hardware. Both the Space Shuttle program and the International Space Station demonstrated that the majority of funds are consumed during operations, not during the design or implementation phases. Therefore, a new way to view space exploration is to treat it primarily as a logistics problem. This is the underpinning of the project on Interplanetary Supply Chain Management where we are teaming with Professor David Simchi-Levi, of MIT's Engineering Systems Division and Department of Civil and Environmental Engineering.

In Project Apollo, each mission was self-contained; none of the missions left anything behind for another mission's use. Future space exploration will use more complex supply networks, on the ground and in space. For example, several orbits and Lagrange points might be employed, and the missions will be intertwined. Lagrange points are stable libration points where the gravitational pull of two bodies such as the Earth and the Moon are in equilibrium. As an example, consider a human mission to the Moon preceded by several robotic and perhaps other human missions. Rather than shipping all supply with the human crew, it might be beneficial to pre-position some of the supply either at the Moon, or at one of the orbits or Lagrange points. Specifically, we are investigating the interplay of the following three fundamental supply chain strategies on space exploration:

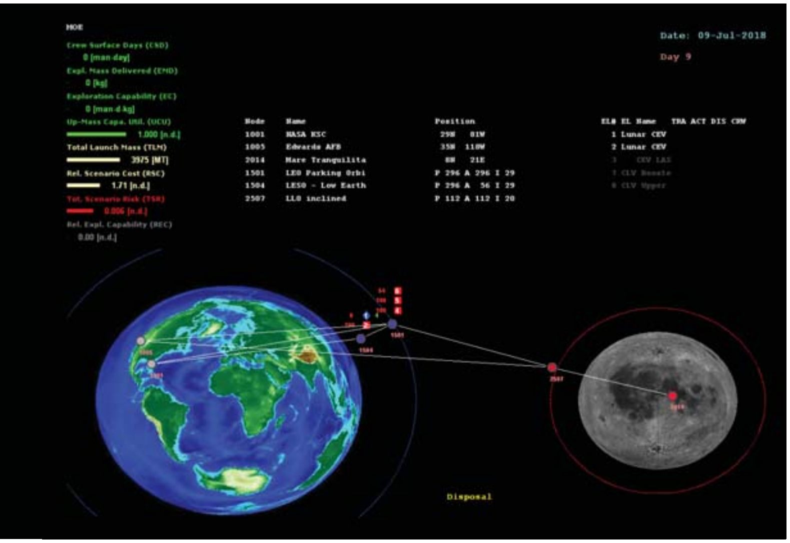
- Pre-positioning — transporting elements and cargo ahead of human crews based on forecasts (push)
- Carry-along — transporting human crews and supplies together
- Resupply — sending supplies to human explorers at remote sites based on actual demand (pull)



Component commonality and modularity, as shown here in these MIT-designed crewed lander and surface habitat concepts, is a key to the affordability of future interplanetary exploration.

The optimal strategy for remote exploration beyond Earth might be a carefully balanced mix of robotic pre-deployments, carry-along as well as on-demand resupply. This translates directly into the terrestrial concept of push/pull boundaries in supply chains were some items are manufactured based on forecasts, while others are only assembled and shipped once actual orders have been received. This is a paradigm shift for NASA, and ways to simulate and optimize missions and campaigns in this way are currently beyond developed in our NASA-funded research project.

Other, yet to be explored, strategies by NASA are in-space refueling and in-situ resource utilization. ISRU focuses on obtaining resources directly from the planetary surface or atmosphere to produce propellants or breathable oxygen. While the necessary technologies have not yet fully matured to perform these functions, their benefits may be significant. An analytical tool to assess such options is necessary much like analytical tools are used in terrestrial supply chains to understand the impact of various supply chain strategies. The primary goal of the Interplanetary Supply Chain Management project is to develop such a comprehensive framework and planning methodology for space logistics.



SpaceNet visualization: planetary surface and orbital nodes are connected by arcs representing launch, in-space trajectories as well as entry-descent-and-landing operations. Elements containing human crews, robotic agents, propellant, collected samples as well as various other supply items, are traveling on these arcs.

SPACENET—A SYSTEMS APPROACH

To evaluate the effect of different supply chain strategies, transportation architectures and vehicle technologies, we developed a software environment called SpaceNet. The basic building blocks are an integrated database of elements (vehicles) and their capabilities, astrodynamical trajectories using both chemical (impulsive) and electrical continuous-thrust trajectories, as well as nodes in the interplanetary system. We distinguish between surface, in-space and Lagrangian nodes. Surface nodes exist on the Earth (such as the spaceport and launch site at the Kennedy Space Center), on the Moon and Mars as well as other bodies of interest such as near-earth-objects. Orbital nodes represent stable orbits around a central body and are characterized by their apoapsis, periapsis and inclination. Lagrangian nodes might lend themselves well for in-space depots and cargo transfer points.

Additionally, we created a new system of supply classification for exploration. The theoretical basis of SpaceNet is the concept of time-expanded networks, which allow simulating and optimizing the flow of elements, crews and associated supplies through the interplanetary supply chain, while taking into account the time-varying nature of launch windows. A time-expanded network is one where static nodes are copied at discrete time steps to capture the four-dimensional space-time underlying space exploration missions and campaigns.

Our focus is on analyzing the requirements for a human return to the Moon, specifically the sortie missions and buildup of a lunar outpost in the 2018-2023 timeframe. However, SpaceNet has proven general enough, so that we are also analyzing alternative strategies for resupply of the International Space Station after the retirement of the Space Shuttle in 2010, as well as opportunities for commercial services for refueling spacecraft in low Earth orbit. An important part of the systems approach underlying SpaceNet is the ability to evaluate the impact of new architectures and technologies on overall measures of effectiveness:

With Professor Olivier de Weck, who holds a little version of the interplanetary supply research team's long-term target — the planet Mars, are team members: Aero-Astro S.M. students Erica Gralla (left) and Sarah Shull, and MIT Leaders for Manufacturing MBA/SM candidate Jason Mellein. (William Litant photograph)

MEASURES OF EFFECTIVENESS FOR SPACE LOGISTICS

- Benefits
  - Crew Surface Days [d]
  - Exploration Mass Delivered [kg]
  - Total Exploration Capability [kg-d]
- Costs
  - Total Launch Mass [kg]
  - Total Scenario Costs [$]
- Risk
  - Total Scenario Risk (scales with the number of required launches, rendezvous-and-dockings, and entry-descent and landing operations in a scenario.)

Additionally, we compute a Relative Exploration Capability metric, which is essentially the product of crew days at a planetary surface and exploration mass delivered, divided by the required total launch mass from Earth's surface. This is a measure of interplanetary supply chain efficiency, a quantity also known as the "divisia" index by traditional economists. When we normalize this ratio by what was achieved in Apollo 17, mankind's last manned mission to the Moon, we can asses the relative impact of new approaches and technologies such as:

- In-situ resource utilization (extraction of oxygen from the lunar regolith, or methane from the Martian atmosphere)

- Refueling of propulsion stages in low Earth orbit with propellant shipped separately by cheaper, potentially less reliable, commercial consumables launchers
- Reconfigurability and commonality of subsystems and components so that they can be used for various functions and scavenged from idle elements as needed
- Closing loops in environmental control and life support systems to reduce the amount of crew consumables needed for long interplanetary flights and extended surface stays
- Trading off relative amounts of consumables, spares, and exploration equipment for build-up and resupply of a lunar or Martian base

The ability to think through and model these complex interactions in a systematic way all the way from subsystem technologies to high level operational scenarios is one of our unique strengths. Moreover, we believe that costs can be reduced by testing many technologies and approaches in Moon- and Mars-analogue environments on Earth, representing a rich area of supporting research.

EFFECTIVE LOGISTICS IS AS MUCH ABOUT INFORMATION MANAGEMENT AND REAL-TIME AWARENESS OF SYSTEM HEALTH AND INVENTORY LEVELS AS IT IS ABOUT TRANSPORTATION

TERRESTRIAL PLANETARY ANALOGS

Such an effort was the 2005 expedition to the Haughton-Mars Project research station on Devon Island. A team of nine MIT researchers went to the Canadian Arctic to participate in the annual HMP field campaign from July 8 to August 12. We investigated the applicability of the HMP research station as an analogue for Moon and Mars planetary macro- and micro-logistics, and collected data for modeling purposes.

At HMP, we also tested new technologies, such as Radio Frequency Identification, and procedures to enhance the ability of humans and robots to jointly explore remote environments. Effective logistics is as much about information management and real-time awareness of system health and inventory levels as it is about transportation. Additionally, a complete inventory of the HMP research station was compiled for future modeling and to create a complete picture of the current state of operations and this was compared against parametric demand models for a lunar base. In a wider sense our model helped establish a benchmark model for efficient operation of a multinational, multi-organizational research base in a remote environment.

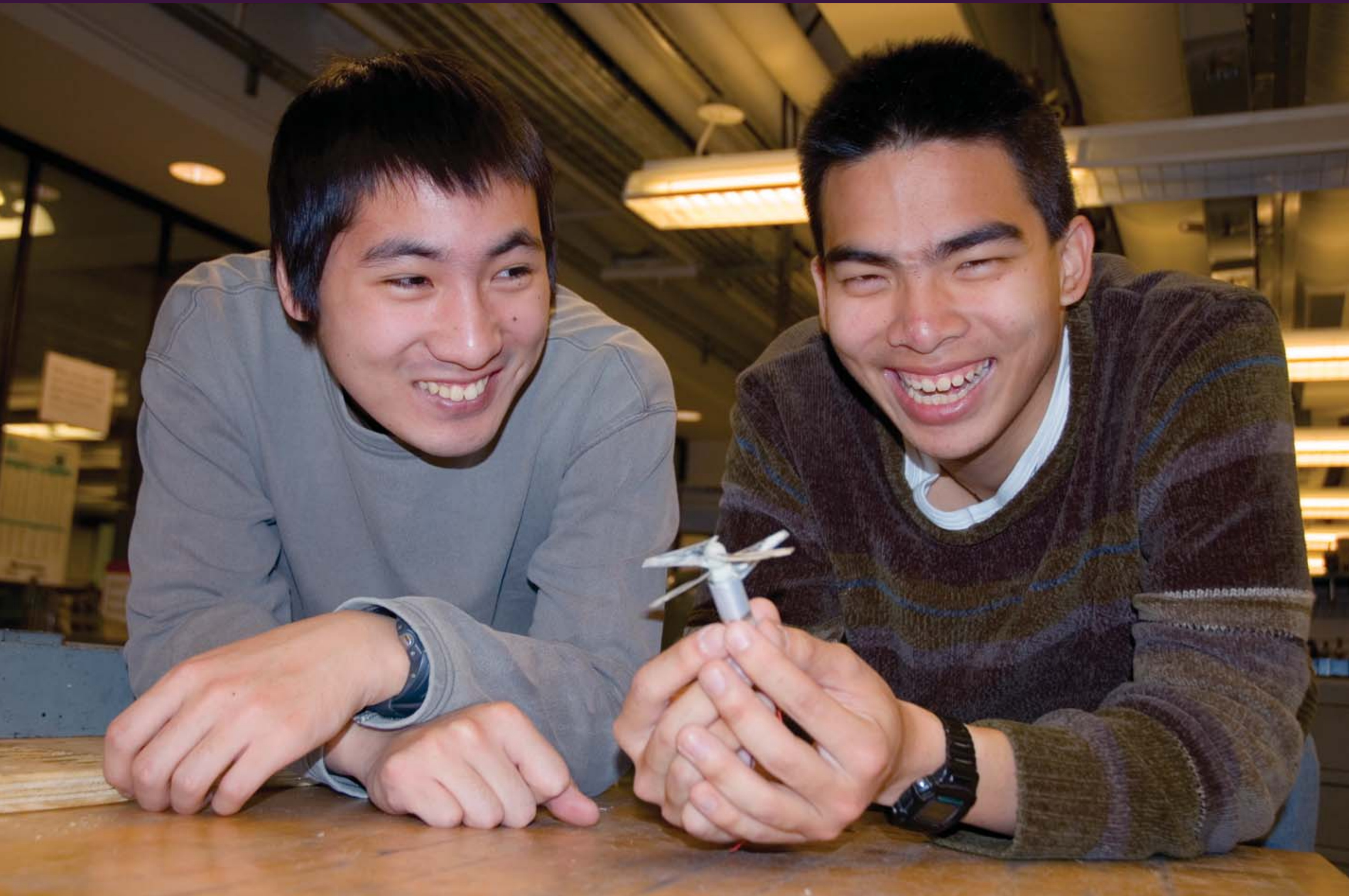
MAKING AN IMPACT

NASA has adopted SpaceNet as a major component of its Integrated Modeling & Simulation infrastructure in support of a strategic analysis capability in the Exploration Systems Mission Directorate. Project Constellation, a major NASA program component that uses this capability, is charged with designing and procuring the next generation of manned spacecraft that will return mankind to the Moon and enable our voyages to Mars and beyond.

Research in interplanetary supply chain management and exploration technologies offers our Aero-Astro faculty, students, and research staff a unique opportunity to take a systems approach in designing sustainable exploration elements and operations. This requires a combination of theoretical modeling, simulation, benchmarking against data from NASA's past and current operations, dedicated field research and cooperation with our partners at Draper, NASA, JPL and industrial companies like Payload Systems Inc. and United Space Alliance LLC. Our students embrace this opportunity. We have combined these research activities with our educational efforts and systems engineering courses at both the graduate (Subject 16.89) and undergraduate levels (Subject 16.83). MIT Aero-Astro is continuing to lead in this new area by developing unique methods and tools for space systems design and logistics, while making a real impact on decisions and technologies that will determine mankind's future in space.

More information about the project is available at: http://www.marsonearth.org

Olivier L. de Weck is an Assistant Professor of Aeronautics and Astronautics and Engineering Systems. He has more than 15 years of military, commercial, and academic experience working on a variety of systems such as the Northrop F-5, F/A-18, Next Generation Space Telescope, Space Interferometry Mission, and various commercial communications satellites. His research focuses on strategic aspects of systems engineering and multidisciplinary design optimization. His Web site is http://deweck.mit.edu, and he may be reached at deweck@mit.edu.



Sho Sato (left) and Ruijie He with the gearless contra-rotating propeller nano air vehicle they developed, built, and tested as 16.62X students. (William Litant photograph)

Independent Research

SMALL TEAMS MAKE EXPERIMENTAL PROJECTS LAB A UNIQUE, POPULAR CAPSTONE

By Jennifer L. Craig and Edward M. Greitzer

Subject 16.62X students choose their topic and advisor, define their experimental problem, develop a hypothesis, create objective statement, identify goals, propose conclusions…it's a tremendous capstone exercise in independent research and a great generator of student enthusiasm.

Juniors and seniors in the Department of Aeronautics and Astronautics complete their degrees with a capstone sequence which serves to both integrate knowledge from various disciplines and to emphasize the Conceive-Design-Implement-Operate context of our curriculum. The Experimental Projects Laboratory (Subject 16.62x in MIT-speak) is one of the choices in this sequence.

The department has other capstone options, but those subjects are usually large ones where a student is one of many team members and the project topic has been specified. In 16.62x, in contrast (and in contrast to almost every other undergraduate subject), students select their own projects from a broad list of faculty suggestions or from student-generated ideas, and work as two-person teams with a faculty or staff advisor. They design, construct, and carry out an experimental project of their own choosing, and report their findings in oral and written formats. The small team size offers opportunity for close contact among students and faculty and staff. The aim is to ensure that students are engaged with an advisor and a project they are enthusiastic about.

The explicit message to the students from the syllabus is:

First and foremost, this is your project. You choose the topic and advisor. Your responsibility is to define an experimental problem, develop a hypothesis, create objective statement(s) and success criteria consistent with the definition of the problem, identify experimental goals, design and construct the apparatus needed to perform the research, conduct the appropriate testing, evaluate the results, and propose relevant conclusions.

STUDENTS ON WHAT THEY LIKE ABOUT SELECTING PROJECTS:

"Being able to choose to do your own project is a terrific opportunity. It gives people the chance to meet a lot of professors and really get a project that intrigues them."

"Independence, being able to choose my own direction."

"Having the experience of managing your own project. Overcoming obstacles and difficulties in project development to finally realize your end goal."

"Working outside of any classroom. Working on a topic that interests you with a close advisor."

The majority of the projects are what might be described as "hard-core Aero-Astro:" assessment of flow uniformity in a supersonic diffuser for a gas dynamic laser, determination of the yield strength of a tank for low cost rockets, or assessment of cockpit display techniques for event avoidance. These increasingly include software and artificial intelligence components. Controlling robot quadruped maneuvers over rough terrain, and monitoring the contents of containers on a space station, are examples this past year's projects.

A number of human factor projects were researched on the driving simulator at the MIT Age Lab as students determined the effects of distraction and stress on driving performance, evaluated flexibility as a function of aging, or defined the readability of screens that provide information to drivers. Although the context may not be an aerospace application, the techniques used, and skills learned, are directly relevant to the aerospace industry.

Several sports-related projects are also typical each term. Recent examples include assessment of a new type of speed skate, determination of optimum finger positions for competitive swimmers, and evaluation of composite baseball bats for increasing batted ball speed.

Even though 16.62x is a laboratory course, the definition of “laboratory” is meant to be inclusive. In fact, it’s not a stretch to say that the laboratory location and type is basically set by the imagination of the students and advisors. Students have carried out experiments in many interesting places: MIT’s Wright Brothers Wind Tunnel, Gas Turbine Laboratory, and Age Lab; an ice rink; a towing tank; Logan Airport; —even atop an MIT building.

In the Wright Brothers Wind Tunnel, 16.62X students Sunny Wicks and Ben Stewart prepare to test a drag-reducing winglet they designed for the top of America’s Cup ship sails. (William Litant photograph)

Three themes tie this diversity of topics and venues together. The first is the student’s experience in learning how to design an experiment. Each team learns how to craft a testable hypothesis about the natural world, outline objectives, develop success criteria, and assess its hypothesis. Developing the ability to design an experiment that enables tangible knowledge discovery is one of the learning objectives of 16.62x; hypothesis formulation and assessment is an important part of the process of developing learning for any organization, and is a critical skill in engineering practice.

The structure and content of the 16.62x cycle follow from this objective. Thus, early in the process, there is strong focus on developing a clear description and an understanding of the hypothesis; an objective or statement of how to assess its correctness; and a statement of how one defines success for this assessment. Further, the design and

STUDENTS ON TEAMWORK AND TEAM MEETINGS

“The team meetings and formal presentations were great. The critiques received ruing these meeting were very helpful. The team meetings were informal and relaxed.”

“Team meetings are very good. They helped us to get back on track and to get objective feedback on our progress. Straightforward and honest feedback is very useful.”

“Teamwork. Cool projects. Yea.”

execution of the experiment is aimed at how the data the students obtain will address testing the hypothesis.

The second theme, and another key learning objective in 16.62x (and in all of Course 16's capstone courses), is teamwork. Collaborative skills on both small and large teams are a big part of succeeding in a project; our faculty know this, and our industry colleagues agree. In 16.62x, students work with a partner as the heart of the larger team comprised of their advisor plus the engineering and communication faculty and technical staff. Participating and functioning as a fast-paced, high-functioning team does not always go smoothly, but the faculty pays close attention to helping students resolve difficulties and to strengthening their skills. We have found that informal team meetings with all the stakeholders present (faculty, advisor, technical staff, and communication instructor) are useful forums. In contrast to conventional presentations, which emphasize progress, the team meetings focus on issues of concern and thus foster in-depth exchange between student and faculty and staff about both technical issues and team dynamics.

STUDENT COMMENTS ON COMMUNICATION AS AN ELEMENT OF EVALUATION

"The final report was also a great opportunity to learn to write collaborative papers."

"I liked making presentations on it as well because everything done was my own work and so I took pride in making it the best possible."

Excellence in written and oral communication is the third overarching theme. The communication-intensive curriculum is an Institute-wide mandate, and 16.62x is one of Course 16's communication subjects. Working with a communication instructor, student teams report their progress through the two semesters in a sequence of written documents and oral presentations that are less like conventional homework and more the kinds of communication in which professional engineers engage. Thus, students learn about audience and persuasion, information organization, informational graphics and data presentation, and how to describe complex engineering decisions. Many 16.62x teams present in various student conferences, and their success rate is high. Over the past six years, our students at the AIAA regional student conference have won first place undergraduate awards in 2005, 2003, 2002, and 2002 as well as second or third place in 2002 and 2000. Again, from the student comments, the idea of presenting communication as an essential part of being an engineer seems to be well accepted

What do our students think about 16.62x? Engineering experimentation can be demanding and sometimes frustrating, but it's one of the few experiences of truly independent work for the students. For some the subject is a research experience that helps shape their professional lives. Our observation is that students finish the Experimental Projects course with a sense of pride and accomplishment about, in the words of one student, "Working as a team on a problem that didn't already have a solution."

Jennifer Craig is a lecturer in MIT's Program in Writing and Humanities and teaches written and oral communication in the Aeronautics and Astronautics Department. She may be reached at jcraig@mit.edu.

Ed Greitzer is the H. N. Slater Professor of Aeronautics and Astronautics. His main research interests are airbreathing propulsion and turbomachinery and he is the MIT lead on the joint Cambridge-MIT Institute (CMI) Silent Aircraft Initiative. He is a Fellow of AIAA and ASME and a member of the National Academy of Engineering.

According to *Aviation and the Environment,* PARTNER's report to Congress, immediate action is required to address the interdependent challenges of aviation noise, local air quality, and climate impact. Environmental impacts may be this century's fundamental constraint on air transportation growth. PARTNER is leading research to address the challenge. (Firefly Productions/CORBIS photograph)

A Global Balance
AVIATION AND THE ENVIRONMENT

By Ian A. Waitz

This past January, the U.S. Congress received a report that began with a stern warning: "Immediate action is required to address the interdependent challenges of aviation noise, local air quality, and climate impacts. Environmental impacts may be the fundamental constraint on air transportation growth in the 21st century." The report summarized the input of a broad range of stakeholders, and was drafted on behalf of the Secretary of Transportation and the Administrator of NASA by faculty and research staff members from the MIT Department of Aeronautics and Astronautics and the MIT Engineering Systems Division.

In the last 35 years there has been a six-fold increase in the mobility provided by the U.S. air transportation system. At the same time there has been a 60 percent improvement in aircraft fuel efficiency and a 95 percent reduction in the number of people impacted by aircraft noise. However, because of the strong growth in demand for air travel, emissions of some aviation-related pollutants are increasing against a background of emissions reductions from many other sources. And, progress on noise reduction has slowed. Millions of people are adversely affected by these side effects of aviation. As a result of these factors and the rising value placed on environmental quality, there are increasing constraints on aviation operations. Airport expansion plans are delayed or canceled due to concerns about local air quality, water quality, and community noise impacts. Military readiness is challenged by restrictions on operations. Efforts to address climate change now include formal international consideration of taxes, emissions trading, and other measures for aviation.

Within this context, the MIT Aeronautics and Astronautics Department is playing a leading role in developing means to balance society's needs for air transportation and environmental quality. Our contributions fall into three categories:

- Leadership of an international center of excellence devoted to aviation and the environment
- Development of tools to enable more effective decision-making with regard to environment-related policy and R&D investments
- Fundamental research contributions to advance understanding of aviation's environmental impacts and identify options for reducing those impacts

PARTNER LEADERSHIP

We are both proud and privileged to lead the Partnership for AiR Transportation Noise and Emissions Reduction, PARTNER (http://www.partner.aero), an FAA-NASA-Transport Canada-sponsored Center of Excellence. PARTNER is a research collaborative comprising 10 universities and almost 50 advisory board members. One of PARTNER's greatest strengths is the advisory board's diversity and inclusiveness. Its members include aerospace manufacturers, airlines, airports, national, state and local government, professional and trade associations, non-governmental organizations, and community groups, united in the desire to foster collaboration and consensus among some of the best minds in aviation. PARTNER pursues technological, operational, policy, and workforce advances to address aviation and environmental challenges.

PARTNER PURSUES TECHNOLOGICAL, OPERATIONAL, POLICY, AND WORKFORCE ADVANCES TO ADDRESS AVIATION AND ENVIRONMENTAL CHALLENGES

In fewer than three years of operation, PARTNER has conducted research and activities including:

- Producing ***Aviation and the Environment,*** the report to the U.S. Congress, which proposes a national vision statement, and recommended actions;
- Successfully testing alternate landing profiles as a no/low-cost means to reduce aircraft noise, fuel consumption, and pollutant emissions;

- Participating in three significant measurement campaigns at U.S. airports to assess and understand the formation of particulate matter from aircraft;
- Collaborating with NASA and industry to study the acceptability of low impact sonic boom noise to enable supersonic flight over land;
- Examining land use, noise, and local development dynamics related to airport encroachment;
- Assessing human health and welfare risks of aviation noise, local air quality, and climate change impacts;
- Developing aircraft and air transportation system simulations to assess policies, technologies, and operational options for jointly addressing air transportation and environmental goals; and
- Developing online resources to better inform the public about aircraft noise issues.

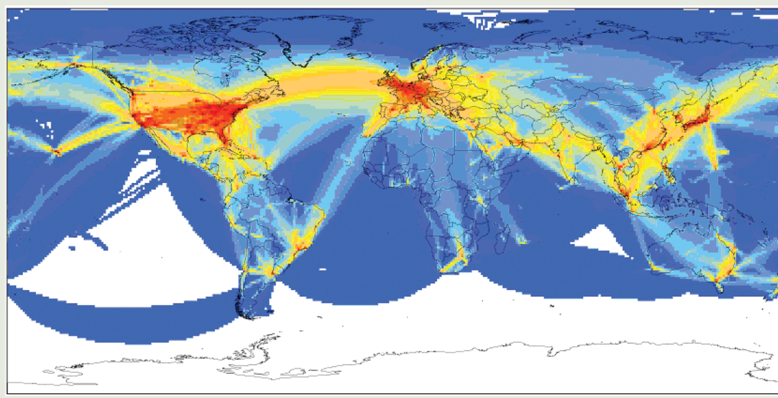
Seven of our research programs are officially designated with the United States Office of Management and Budget as potentially "leading to highly influential scientific disseminations." This designation is reserved for federally sponsored research programs with the potential to influence greater than $0.5 billion in federal expenditures (among other criteria). Special peer

RESEARCH HIGHLIGHT

System for Assessing Aviation's Global Emissions

The System for Assessing Aviation's Global Emissions is a high fidelity computer model used to predict aircraft fuel burn and emissions for all commercial flights globally in a given year. The model is capable of analyzing scenarios from a single flight, to operations on airport, country, regional, and global levels. SAGE can dynamically model aircraft performance, fuel burn and emissions, and capacity and delay at airports, as well as forecasts of future scenarios. SAGE has also been used to analyze the sensitivity of those inventories to changes in operational, policy, and technology-related scenarios.

The Volpe National Transportation Systems Center, MIT, and the Logistics Management Institute developed SAGE for the FAA Office of Environment and Energy. MIT's principal contributions were the development of the aircraft and engine performance, fuel burn and emissions models, as well as assessment of uncertainty for SAGE as a whole. The United Nations Intergovernmental Panel on Climate Change recommends SAGE as a high-fidelity method for reporting national emissions inventories for aviation for obligations under the United Nations Framework Convention on Climate Change. SAGE has also supported the work of the International Civil Aviation Organization, Committee on Aviation and Environmental Protection, appearing to date in 15 ICAO/CAEP information papers and other documents.



This output from the FAA System for assessing Aviation's Global Emissions (SAGE) shows the world-wide distribution of aircraft carbon dioxide emissions for 2000.

LEADERSHIP

Aviation and the Environment:
REPORT TO CONGRESS

PARTNER drafted the recent Report to the United States Congress: Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions.

Over one hundred stakeholders participated from 38 organizations spanning the aerospace industry, NASA, FAA, the Environmental Protection Agency (EPA), the Department of Commerce (DOC), the Department of Defense (DoD), academia, state and local governments, and community activists.

Perhaps the most significant accomplishment reflected in the report is a proposal for a National Vision Statement for Aviation and the Environment. This vision statement is supported by all of the fifty-nine stakeholders who directly participated in drafting it. The National Vision specifies absolute reductions in significant health and welfare impacts from many aviation sources, reduced uncertainty in understanding other impacts, and global leadership for the U.S. aerospace enterprise in jointly addressing aviation mobility and environmental needs.

To achieve this challenging vision, the report recommends three actions. The first is to promote coordination and communication among stakeholders. The second is to develop more effective tools and metrics for guiding policy decisions and for planning research investments. The third is to establish a vigorous program to develop specific technological, operational and policy options that support a balanced approach to long-term environmental improvements. These recommendations are the foundation for the Environmental Objectives in the Next Generation Air Transportation System plan. The complete report is available for download at http://www.partner.aero.

This image depicts the relationship between the recommended actions and the National Vision for Aviation and the Environment. Technology, Operations and Policy represent a balanced approach to addressing aviation mobility and environmental needs. These are placed in an inverted triangle to signify that the balance is dependent on the supporting elements of Communication and Coordination, and Tools and Metrics. It is only with all three of these elements in place that the National Vision of absolute reductions, reduced uncertainty and global leadership will be achieved.

review processes are required before the federal government can adopt and disseminate the results of such research programs.

RIGOROUS GUIDANCE FOR DECISION-MAKERS

MIT's most prominent role within PARTNER is developing tools that provide rigorous guidance to policy-makers who must decide among alternatives for addressing the environmental impacts of aviation. We are collaborating with an international team to develop aircraft-level and aviation system level tools to assess the costs and benefits of different policies and R&D investment strategies. Currently, environmental policy assessments are largely compartmentalized, focusing, for example, solely upon noise, local air quality, or climate. Often the full economic costs and benefits, and the complex interdependencies, are not considered when evaluating policies and prioritizing research investments. In practice, well-intended changes in one domain may produce unintended negative consequences in another.

For example, in 2004 the International Civil Aviation Organization adopted new certification standards for aircraft engine NO_x emissions. The new standards represent a 12 percent increase in stringency to be introduced in 2008 and are designed to mitigate the local air quality impacts of aviation. ICAO estimated the cost of this increase in stringency to be approximately $5 billion. Aircraft and engines designed to meet this standard are expected to make compromises on fuel burn and weight, and thus, on climate and noise impacts. What will be the performance and environmental characteristics of future aircraft under different policy alternatives and market scenarios? How should we balance competing environmental objectives? What is a unit of climate change impact worth in terms of a unit of noise impact, or a unit of local air quality impact? And, how should we weigh these impacts against the economic costs of the policy, costs that ultimately are passed on to consumers of aviation services and can influence the profitability of aviation producers and producers in related industries?

WELL-INTENDED CHANGES IN ONE DOMAIN MAY PRODUCE UNINTENDED NEGATIVE CONSEQUENCES IN ANOTHER

The foundation for our work is the development of environmental and economic systems models that simulate aircraft and engine design practices, airline and consumer behavior, air transportation operations, noise, local air quality and climate impacts, and then monetize all of these effects using established practices for valuation of health and welfare impacts. Many components of our simulations are carried out using legacy codes, and the degree of fidelity of these codes can be staggering. For example, we model 450 individual aircraft types, track the current world fleet by tail number (80,000 airplanes), fly all flights in each year on detailed mission profiles (30 million flights per year), develop noise footprints, and assess local air quality impacts at 35,000 airports worldwide, estimate climate change impacts using impulse response functions derived from general circulation and carbon-cycle models of the global climate, and assess health and welfare impacts using concentration-response curves from epidemiological studies, noise and health valuation data, and detailed census and socio-demographic information.

Within this work are some grand challenges that we are only starting to address. For example, given the complexity of the tools we are using to simulate the future behavior of the air transportation system and its economic and environmental impacts, how can we rigorously assess uncertainty? Moreover, how can we use our understanding of the sources for this uncertainty to actively manage the fidelity of our tools in a way that directly responds to a range of policy-maker needs? As we progress towards providing more rigorous information to policy-makers, how should the national and international processes for negotiating policy decisions be changed? And how should the regulatory structures be changed to reflect the interdependent character of the air transportation system and its relation to different environmental impacts?

Ultimately, we hope to enable better policy decision-making by simultaneously evaluating the interdependent environmental impacts of the air transportation system, while providing a more complete assessment of costs and benefits. We benefit from working directly with the key U.S. policy-makers. Indeed, our relationship with our sponsors is not one marked by a few technical reports and site visits per year, but rather as many as five teleconferences and 50 emails each week. This direct engagement with the policy-making community presents both opportunities and challenges. The opportunity is that our analyses and simulations will influence multi-billion dollar decisions that can have profound and far-reaching impacts. The challenge is that our work is subject to a high level of political sensitivity and scrutiny. All of this adds to the fun and excitement.

ULTIMATELY, WE HOPE TO ENABLE BETTER POLICY DECISION-MAKING

FUNDAMENTAL PROBLEMS, UNIQUE OPPORTUNITIES

Our ability to simulate the entire aviation system and its environmental impacts provides us with a unique opportunity to identify fundamental research problems. As an example, while aircraft contribute only 0.01 percent to the U.S. national particulate matter inventory, PM has a relatively high health impact (health costs are around $60,000/metric ton, versus $2000/metric ton for NO_x and $5-$125/metric ton for CO_2). Our assessments show that the health and welfare impacts of aviation PM are similar to those of NO_x. However, while much is known about aircraft NO_x emissions, little is known about PM emissions and their relationship to engine design and operating conditions. Emissions from fossil fuel combustion typically contain not only hard particles (soot), but also minor fractions (parts per million and parts per billion) of gases such as SO_3. SO_3 reacts with water to form H_2SO_4 and then condenses — forming very small volatile particles (these particles range in size from several nanometers to tens of nanometers in diameter). These very small particles may pose the greatest health concern because they can be entrained deep into our lungs. Fine volatile particles may account for as much as half of the total PM mass emissions and are regulated under the U.S. Clean Air Act, and are not unique to aviation. However, in contrast to those of automobiles and powerplants, aircraft engine emissions are exhausted at higher temperatures, so the nucleation, condensation and coagulation of the volatile particles differ. Measurements have only just begun to characterize these differences. We have contributed

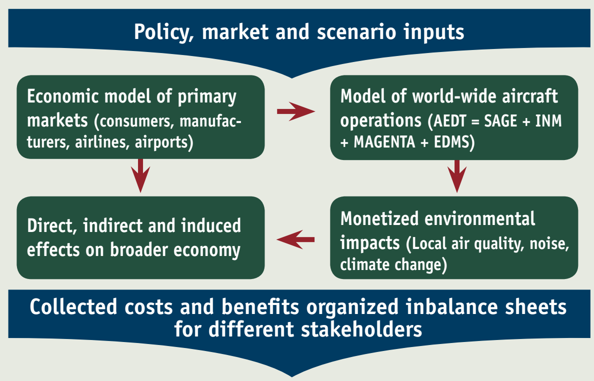
RESEARCH HIGHLIGHT

Aviation Environmental Portfolio Management Tool

In order to select environmental policies and R&D options that balance society's economic and environmental needs, national and intergovernmental agencies must have the ability to assess the complete impact of each suggested policy, accounting for potential interdependencies among market conditions, aircraft technology, air transport operations and local air quality, noise and climate change impacts. To accomplish this, the Federal Aviation Administration Office of Environment and Energy has launched a project to create a suite of software tools. The suite's economic analysis function is known as the Aviation Environmental Portfolio Management Tool. MIT is leading the international APMT development team that includes participants from BB&C Consulting, Georgia Institute of Technology, MITRE-CAASD, MVA, Vital Link Policy Analysis, Volpe National Transportation Systems Center, and Wyle Laboratories.

APMT takes aviation demand and policy scenarios as inputs, and simulates the behavior of aviation producers and consumers to evaluate policy costs. Detailed operational modeling of the air transportation system provides estimates of the emissions and noise outputs. Then, a benefits valuation module is used to monetize the health and welfare impacts of aviation noise, local air quality and climate effects. These modules jointly enable a cost-benefit analysis of policy alternatives.

The effort to develop an APMT prototype began in February of 2006. We are working to deliver a fully-functional simulation by the end of this year for consideration by the International Civil Aviation Organization, Committee on Aviation and Environmental Protection in 2007.

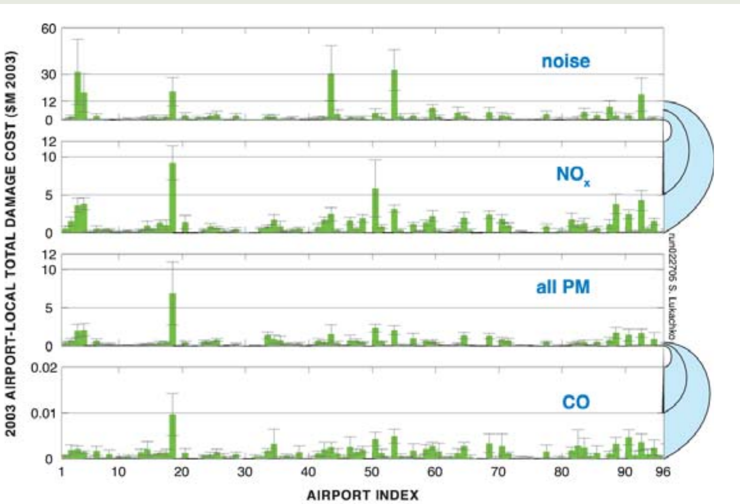


RESEARCH HIGHLIGHT

HEALTH AND WELFARE RISKS OF AVIATION ENVIRONMENTAL EFFECTS

We have developed a probabilistic multi-attribute impact pathway analysis for valuing, in a commensurate way, the different risks to health and welfare from aviation. Assessments are based upon explicit valuations of the environmental costs of noise, local air quality, and climate change, enabling firms and government agencies to differentiate among new technologies, allocate limited budgets for research and mitigation, and evaluate the comparative efficacy of policy options. For each step, from demand estimation to the evaluation of willingness to pay for environmental amenities, best practice methods and data are employed. Uncertainties are treated probabilistically using Monte Carlo simulation to generate cost distributions.

An example result is shown below for the 96 largest airports in the United States. (Note the different monetary scales.) Our results point to three conclusions. First, aviation particulate matter emissions result in air quality impacts roughly similar to aviation NOx emissions. Second, aviation noise and emissions impact at the airport local scale lead to similar damages across the majority of airports except for a few locations where aviation noise is dominant. Third, including the costs of climate change attributable to aviation (not shown), emissions are associated with higher damage costs when compared to noise.



Noise and local air quality damage costs by airport for 2003.

to understanding the differences by developing (in collaboration with Aerodyne Research Incorporated) detailed numerical simulations of the fluid mechanics, chemistry, and particle microphysics within the engine, the exhaust plume, and in the sampling probes and lines employed in measurement campaigns. Our accomplishments include identifying an important role for turbine design (in addition to combustor design) in determining emissions of SO_3. We also made the first estimates of the effects of engine design and operating conditions on volatile PM emissions, and recently demonstrated that some experimental techniques used to assess PM emissions must be improved.

BALANCING SOCIETY'S NEEDS

Through these and other research efforts, MIT Aero-Astro is playing a leading role in developing means to balance society's demand for air transportation and environmental quality. Our work requires a challenging combination of breadth and depth, including knowledge of combustion, emissions, and noise; propulsion and aircraft system engineering; transportation system design and operation; environmental sciences (*e.g.,* atmosphere, biosphere); health sciences (*e.g.,* epidemiology and toxicology); environmental and aviation law; environmental economics; policy and business decision-making; and risk and uncertainty. It is through the unique combined talents of our graduate students, research staff members, and national and international collaborators that we address these problems.

Ian A. Waitz is a Professor in the MIT Department of Aeronautics and Astronautics and 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

In Aero-Astro's Wright Brothers Wind Tunnel, graduate student Anna Mracek, recent alumnus Dr. Samuel Schweighart (left), and doctoral candidate Carl Dietrich run tests on a model of Transition, the roadable airplane they hope to manufacture. (William Litant photograph)

Transition

THIS PERSONAL VEHICLE'S FUTURE IS IN THE AIR — AND ON THE ROAD

By Carl Dietrich

Common wisdom suggests that any vehicle design combining two disparate modes of transportation — flying and driving — will always result in a compromise that will do each task poorly, and, consequently, be unattractive to the marketplace. Advocates say that the potential benefits of such a vehicle could outweigh the performance compromises. Of course, such a bimodal vehicle presents a tremendous engineering challenge, and the devil is in the details. Only those details of the compromise will determine which school of thought is correct.

In 1918, Felix Longobardi was issued the first U.S. patent for a vehicle capable of flying through the air and driving on the ground. In the ensuing 82 years, there have been nearly 100 published designs for vehicles that combine some of the features of a car with some of the features of an airplane. Some of these vehicles were actually built, and a handful of prototypes were certified by the FAA. However, all of these ventures were commercial failures: the compromises that were sufficiently simple to prototype and certify, were operationally impractical. To date, not one of them has been successfully developed and certified.

Three graduate students/pilots from the MIT Department of Aeronautics and Astronautics believe that now is the time to make a truly practical dual-mode general aviation vehicle. They think that they know what sort of compromise will find commercial success. Anna Mracek, a graduate student in TELAMS; doctoral candidate Carl Dietrich, winner of the 2006 Lemelson-MIT Student Prize; and recent alumnus Dr. Samuel Schweighart have formed a venture they call Terrafugia — derived from the Latin for "escape the earth" — to develop a novel roadable aircraft design for the general aviation community.

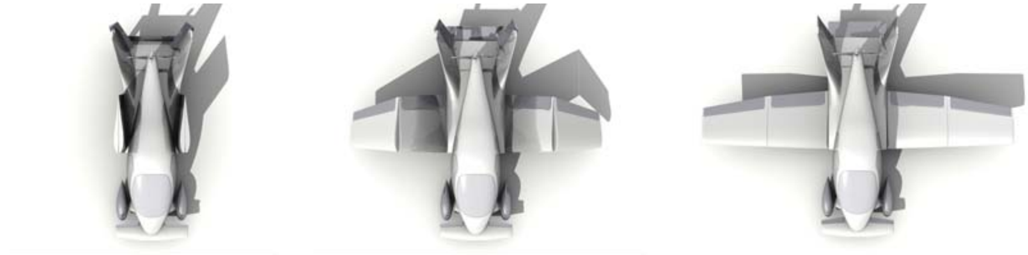
Why would they see a need for a vehicle with implicitly compromised performance? To put it simply, they see a demand from the general aviation community for this type of vehicle.

In 2002, Troy Downen and Professor R. John Hansman of the MIT Department of Aeronautics and Astronautics published “User Survey of Barriers to the Utility of General Aviation.” In their paper they identified four primary barriers:

- Weather
- Expense
- Mobility at destination
- Doorstep to destination travel time

Expanding the general aviation market will be enabled by vehicles or systems that mitigate the impact of these barriers. Building a vehicle with just improved performance (faster and perhaps marginally more efficient) than existing GA aircraft certainly attacks the travel time barrier—and this has been the normal progression of GA to date. The market for single engine piston aircraft has fluctuated tremendously over the years, but advances in performance have not fundamentally expanded the market for new GA single engine planes. According to pilots—the primary GA users—improved performance does little to reduce the first three barriers to the more widespread use of general aviation.

The introduction of a practical roadable aircraft could directly reduce the effects of all four barriers (this is axiomatic—if it is practical, it will, by definition, address these barriers). An integrated roadable aircraft clearly improves a pilot’s mobility at their destination—eliminating



any dependence on a rental car or taxi infrastructure, which does not exist at the vast majority of the 5,000-plus public use GA airports across the country. Even if these vehicles suffer a performance penalty in the air, door-step-to-destination travel time could also be improved because of elimination of a need to secure another vehicle at the destination, and transfer people and bags between air and ground vehicles. Eliminating need for transportation changes at the destination airport would translate directly into time savings due to reduced planned time buffers.

IF A STORM THREATENS, THE PILOT CAN DIVERT TO THE NEAREST FIELD AND DRIVE SAFELY UNDER THE WEATHER

A potential for reduced expense is an advantage of the new FAA light sport aircraft rule. This rule substantially reduces the barriers to certification of certain GA aircraft that fit within specified performance limitations. If there is a marked need for this sort of vehicle, costs per vehicle may be reduced as manufacturing rates increase in response to the demand. Finally, the biggest advantage of a roadable aircraft is a new relative insensitivity to weather conditions: if a storm threatens, the pilot can divert to the nearest field and drive safely under the weather. This fundamental improvement in safety by giving VFR pilots more acceptable options for safe travel, is perhaps the biggest advantage of the a road-worthy aircraft.

Terrafugia anticipates that pilots of the Transition Personal Air Vehicle—the name chosen for the new airplane-car—will be less-susceptible to "get-there-itis" (one of the most common reasons pilots put themselves in bad situations) than their GA counterparts. This safety

advance is really an implementation of a combination of technologies based on an understanding of pilot psychology. Most GA accidents could have been avoided if the pilot had made at better decision at some point in time. By giving pilots more acceptable options for how to get where they want to go, Terrafugia believes that they will help GA pilots make better decisions — and save lives in the process.

Terrafugia is developing the Transition to satiate this perceived need in the general aviation community for a dual use vehicle. The Transition will be a two-place roadable aircraft designed to follow both National Highway Traffic Safety Administration guidelines and the newly implemented FAA Light Sport Aircraft consensus standards. These new FAA regulations substantially reduce the barriers to bringing a certified "light sport aircraft" to the general aviation market.

Recent alumnus Dr. Samuel Schweighart (left), doctoral candidate Carl Dietrich, and graduate student Anna Mracek, with Transition, the roadable airplane they hope to manufacture. (William Litant photograph)

Terrafugia will benefit from more resources than its predecessors in addressing the roadable aircraft compromise. Since its inception shortly after the official announcement of the light sport aircraft/sport pilot rule in September of 2004, Terrafugia has drawn technical and business lessons from previous attempts. It has developed four key pieces of intellectual property (patents pending). Vortex-lattice computer models have been built, more than 50 iterations of the vehicle's outer mold-line analyzed, and currently a second round of wind-tunnel data is being collected in Aero-Astro's Wright Brothers Wind Tunnel. Two pilots from the MIT Sloan School of Business have joined the core team, and Terrafugia is assembling a top-notch board of technical and business advisors from the ranks of the MIT Department of Aeronautics and Astronautics, the MIT Entrepreneurship Center, and the MIT Venture Mentoring Service.

The Terrafugia team and the Transition vehicle are examples of Aero-Astro at its best: an exciting, visionary project, assembled by a talented crew that's benefited from the unique education and resources only MIT offers.

Carl Dietrich, a non-current private pilot, received both B.S. '99 and M.S. '03 degrees from the MIT Department of Aeronautics and Astronautics where he is currently a doctoral candidate. Dietrich was winner of the 2006 Lemelson-MIT Student Prize for his inventive career. He may be reached at chipd@mit.edu. More information about Terrafugia and the Transition can be found at http://www.terrafugia.com.

Students in the Aerospace Computational Design Laboratory develop and use computational methods to study a range of problems. One ACDL project involves a team of students simultaneously developing computational fluid dynamics software to simulate flows like that around the blended wing body aircraft appearing on the monitors. (William Litant photograph)

COMPUTATIONAL ENGINEERING IS GROWING, AND AERO-ASTRO IS IN THE THICK OF IT

By David Darmofal, Jaume Peraire, Raul Radovitzky, and Karen Willcox

Richard Whitcomb, one of the most influential aerodynamicists of the 20th century, was well known to design airfoil sections by hand. He would take a file into the wind tunnel at NASA Langley and modify an airfoil's shape based on his understanding of aerodynamics and on the data he had just collected. Some 50 years later, airfoil design is now dominated by computational methods leading to the replacement of the wind tunnel with a laptop computer for this problem. In fact, the application of computational methods to engineering problems, that is, computational engineering, is a discipline with a much wider scope than airfoil design and sees application throughout all fields. There're some particularly interesting research and educational activities happening in the Department of Aeronautics and Astronautics in this rapidly growing discipline.

Intensive computation for simulation and optimization has become an essential activity in the design and operation of complex systems in engineering. Thus, while computational engineering is a discipline in itself, it advances all engineering. The recent National Research Council report "Research Directions in Computational Mechanics" points out that revenues from simulation and optimization software products are in the billions of dollars, and the overall economic impact of these products is in the trillions of dollars. Despite this considerable development, the same report predicts that the next decade will experience an explosive growth in the demand for accurate and reliable numerical simulation and optimization of complex systems.

Since the early days of computational mechanics, the aerospace community has been at the forefront of computational engineering. Not surprisingly, NASA has played a major role in the development of the early finite element codes for structural mechanics (e.g., NASTRAN) as well in the development of computational fluid dynamics. Traditionally, the aerospace industry has pioneered the use of the latest computational methods. In many cases aerospace companies have developed highly sophisticated in-house capabilities through alliances with universities and research institutions. The origin of the more recent paradigms on multidisciplinary design and optimization can also be traced to the same community. Within our department, computational methods are used in almost all research efforts. However, the advancement of computational methods for aerospace design is the focus of the Aero-Astro Aerospace Computational Design Laboratory.

COMPUTATIONAL ENGINEERING CHALLENGES

When airfoils are operating at, or near, their intended design conditions, computational fluid dynamics models can accurately approximate the aerodynamic flows in just a few seconds on a laptop computer. Thus, in much the same way that Whitcomb used his file and a wind tunnel to design airfoils, a modern aerodynamicist can use CFD methods to quickly try new airfoil design concepts. Aero-Astro Professor Mark Drela's MSES software takes this modeling capability a step farther, and can automatically optimize airfoil shapes to achieve desired performance characteristics.

However, for problems that are more complex than airfoil design, computational methods are hindered by a combination of effects including:

- **Uncertainty:** Computational simulations begin with a set of model equations. These model equations (even if solved exactly) are only an approximate representation of reality. Furthermore, a computational model is typically constructed by discretizing these model equations. For example, to simulate the flow around an aircraft using a finite element method, the region around the body will be discretized into many small elements and the solution in each element will be assumed to be a polynomial. As the number of elements and/or the order of the polynomials in each element are increased, a well-constructed simulation will converge to the solution of the model equations. However, given that computational resources are finite, discretization errors will be present. Thus, modeling and discretization errors combine to create uncertainty in the validity of the computational simulation. As problems increase in complexity, these uncertainties typically increase as well.

- **Automation:** For complex, three-dimensional problems, in particular those with complicated geometry, the process of discretizing the problem can require significant human interaction. For example, the generation of meshes appropriate for simulation of flow around aircraft or in jet engines can require weeks of engineering effort. The main cause for this time requirement is that the process of generating meshes for complex geometries is far from robust and requires human intervention to circumvent problems. In fluid dynamic applications, the problem of meshing robustness is especially acute for flows with boundary layers that require thin elements near all surfaces. For comparison, once a mesh is generated, the simulation on these meshes typically can be completed in a day or two on a state-of-the-art computer. This lack of robustness leads to a lack of automation. Currently, it is not possible to go from engineering concept to computational simulation in a timely manner for complex problems.

- **Computational cost:** The cost of performing computational simulations is driven by the available computer speed and memory, and the choice of computational algorithm. As raw computer speed has continued to increase, so has the complexity of feasible simulations. In addition to speed gains for a single computer, state-of-the-art computational simulations are almost exclusively performed on clusters of interconnected computers. For example, the world's fastest supercomputer is the BlueGene/L at the Department of Energy's Lawrence Livermore National Laboratory. Manufactured by IBM, this computer has more than 100,000 processors, and is the only computer to achieve more than 100 teraflops on a standard linear algebra test case. (Flops is the number of FLoating point OPerations per Second, so a teraflop is a trillion floating point operations per second.) To use these clusters effectively, new computational algorithms are required that attempt to reduce the time spent communicating between each processor while increasing the time spent operating on the data within each processor. Interestingly, over the past 30 years, improvements in computational algorithms have contributed equally with improvements in computer hardware towards advances in simulation complexity.

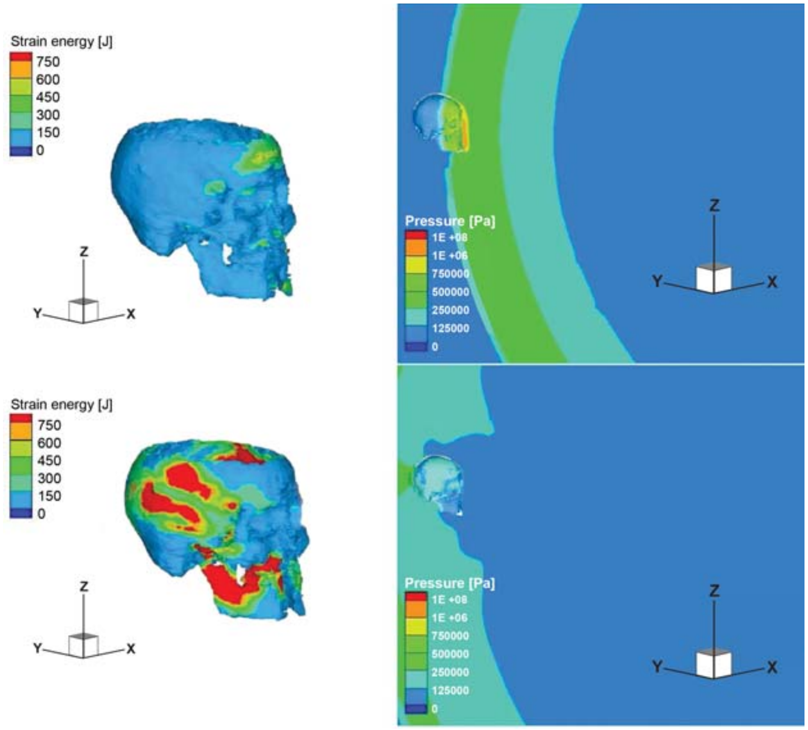
COMPUTATIONAL ENGINEERING RESEARCH

The Aero-Astro Department has numerous research efforts in computational engineering; we highlight a few of them here.

- **Multiscale Modeling for Material Design:** Material design has been largely based on empiricism. The main reason for this situation has been a lack of systematic strategies to design materials from a set of functional requirements: the connection between microstructure and performance is a priori unknown and has seldom been established. However, a critical societal need exists to develop new materials for a wide range of applications

  Multiscale materials modeling combined with high-performance simulation provides a rational approach for material design. Led by Professor Raul Radovitzky, the department's computational solid modeling group is successfully applying this modeling paradigm to a variety of problems including the description of anomalous plastic deformation in nanocrystalline metals, dynamic response of polycrystalline metals, nanoscale plasticity in biomimetic materials with extreme fracture toughness, and high-rate response of soft biological tissue and human organs to blast loads. By way of example, the following figure shows our efforts to describe blast effects on the human brain using our coupled blast-structure interaction capability, tissue models and realistic geometries from 3D magnetic resonance imaging. The figure shows two snapshots at t = 1.13ms and t = 1.74ms of a simulation of the interaction of a blast wave produced by the explosion of 1.5Kg of TNT at a stand-off distance of 1.5 m on a human cranium. The blast delivers a pressure wave with an overpressure of approximately 5 atm at the point of impact with the cranium. Stress wave propagation and multiple reverberations inside the skull lead to peak strain energy densities in excess of 750 J m−3.

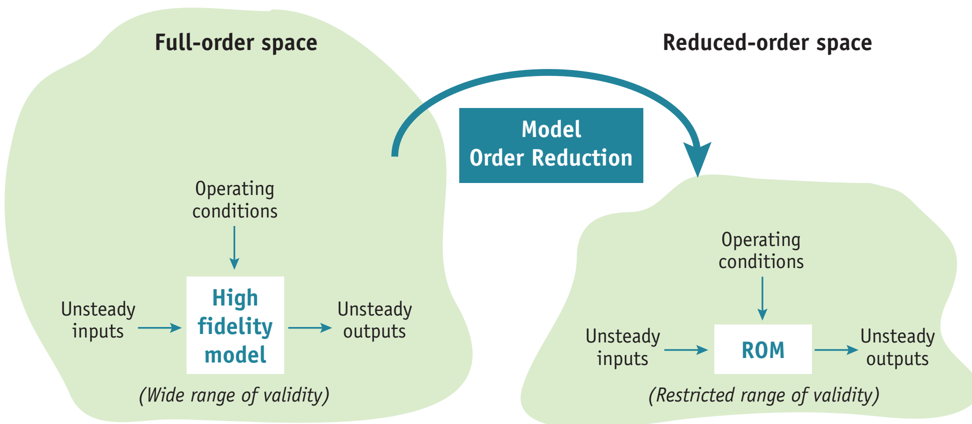
- **Model reduction for real-time simulation and optimization**: While the use of high fidelity computational models such as CFD is widespread for analysis and design, an emerging challenge is real-time simulation and optimization. The need for real-time simulation is critical for many applications, including emergency response to natural disasters, industrial accidents, and terrorist attacks, control of dynamical processes and adaptive systems, and interactive design of complex systems. The challenge is to develop models of sufficient accuracy than can be used in real-time decision making.



Using a high-fidelity, finite-element-based method, the interaction of a blast wave from a 1.5 Kg TNT explosion with a human cranium is shown at the initial (top) and later (bottom) stages. On the left, the strain energy distribution on the cranium surface is shown; on the right, the pressure perturbations on the cranium and in the field are shown.

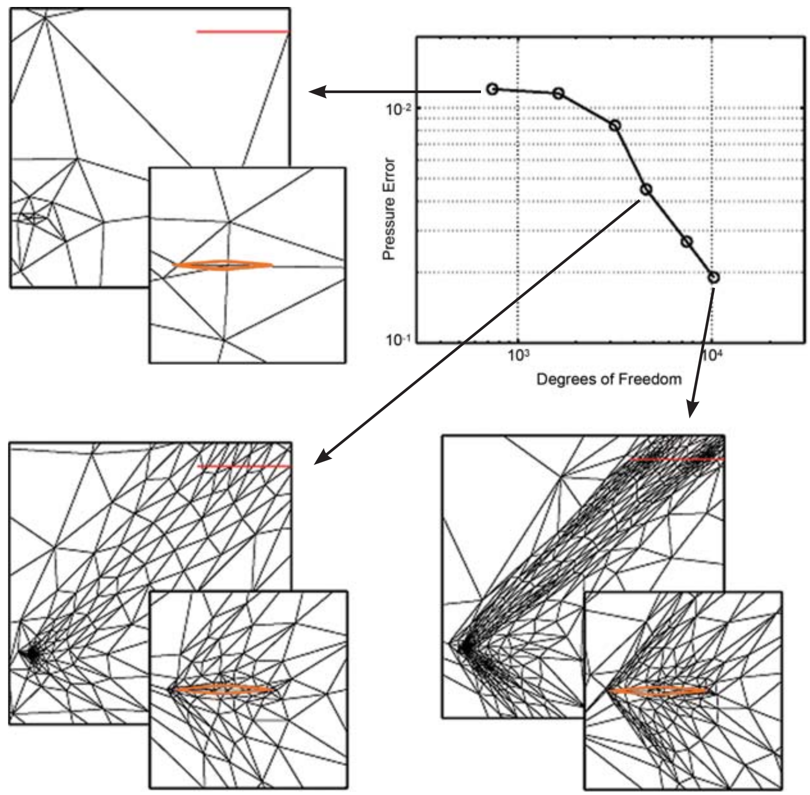
One approach to developing an accurate, real-time modeling capability is known as model reduction. In general terms, model reduction entails the systematic generation of computationally-efficient representations of large-scale systems that result, for example, from high fidelity discretization of partial differential equations. More specifically, a reduced-order model can be obtained by using the structure of the governing equations and mathematical techniques to identify key elements of the system input/output behavior. In the past decade, reduction methodology has been developed and applied for many different disciplines, including controls, fluid dynamics, structural dynamics, circuit design, and weather prediction. Model reduction research in ACDL, led by Professor Karen Willcox, has focused on the development and application of model reduction methodology for aerospace problems that include compressor blade aeroelasticity, supersonic inlet flow dynamics, and active flow controller design. Our current projects include development of a new methodology that creates reduced-order models for inverse problems. We are applying this methodology to a data-driven framework for real-time reconstruction of hazardous events from sparse measurements.

- **Next-generation CFD Algorithms:** A major ACDL research area within the Aerospace Computational Design Laboratory is the development of next-generation algorithms for computational fluid dynamics. Led by Professor Dave Darmofal, Bob Haimes, and Professor Jaime Peraire, and supported by the Air Force, NASA, Boeing, and Ford, the goal of this research is to improve the aerothermal design process for complex configurations by significantly reducing the time from geometry-to-solution at engineering-required accuracy. A key ingredient in our approach is the use of adaptive methods to



Model reduction uses mathematical techniques to create a reduced-order model that replicates the input/output behavior of a high-fidelity model over a restricted range of validity.

automatically control the discretization error. The basic premise of an adaptive CFD method is to simulate the flow on an initial mesh, estimate the error contributed by each element within the mesh, and refine the mesh in elements that most contribute to the estimated error. A novel aspect of our adaptive method is that it seeks to control the impact of discretization error on outputs of engineering importance such as lift, drag, or moments. Thus, engineering decisions can be made with increased confidence that key outputs have been accurately estimated. For certain classes of problems, we have moved beyond error estimates and can bound the output error.



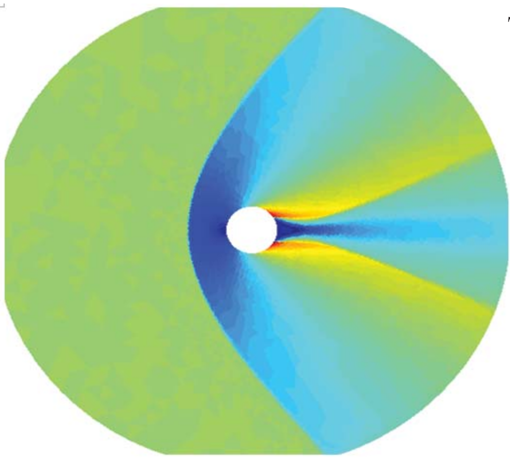
Example of an adaptive calculation of the supersonic flow around an airfoil. The initial mesh is adapted to accurately estimate the farfield pressure distribution on the red line. The adaptive method uses an approach in which the elements are not required to conform to the shape of the body (shown in orange).

TEACHING COMPUTATIONAL ENGINEERING

Computational engineering is a multidisciplinary field requiring knowledge of mathematics, computer science, and engineering. At the undergraduate level, we have developed 16.901 Computational Methods in Aerospace Engineering. The learning objectives for this subject are for the students to attain:

- Conceptual understanding of computational methods commonly used for analysis and design of aerospace systems

- Working knowledge of computational methods including experience implementing them for model problems drawn from aerospace engineering applications
- Basic foundation in theoretical techniques to analyze the behavior of computational methods



Mach 2 supersonic flow passed a cylinder simulated by students in 16.901 using a finite volume method.

This subject's enrollment has grown in size each year. In the spring of 2006, more than 40 students were enrolled. During the semester, students gain hands-on experience with computational methods by implementing them to solve various aerospace-derived problems; for example, in 2005, students developed a finite volume method to approximate the supersonic flow over a circular cylinder.At the graduate education level, a new interdepartmental Master of Science program in Computation for Design and Optimization has been created. The CDO interdisciplinary program provides a strong foundation in computational approaches to the design and operation of complex engineering and scientific systems. Furthermore, the program provides a focal point for the large computational engineering research community at MIT. The current program has more than 20 affiliated faculty members from the schools of Engineering, Science, and Sloan. Aero-Astro is well represented: the program co-director is Jaume Peraire; and Dave Darmofal, Olivier de Weck, Raul Radovitzky, and Karen Willcox are affiliates. The department offers several graduate subjects in computational engineering, all of which are also a part of the CDO program. These include:

- 16.225J: Computational Mechanics of Materials
- 16.888J: Multidisciplinary System Design Optimization
- 16.910J: Introduction to Numerical Simulation
- 16.920J: Numerical Methods for Partial Differential Equations
- 16.930: Advanced Numerical Methods for Partial Differential Equations

Computational engineering has changed the way aerospace design is conducted. As the use of computational engineering spreads, new challenges will continue to arise. We look forward to addressing these challenges.

David Darmofal is an Associate Professor of Aeronautics and Astronautics and a MacVicar Fellow. Jaume Peraire is a Professor of Aeronautics and Astronautics, director of the Aerospace Computational Design Laboratory, and co-director of the Program in Computation for Design and Optimization. Raul Radovitzky is the Charles Stark Draper Associate Professor of Aeronautics and Astronautics. Karen Willcox is an Associate Professor of Aeronautics and Astronautics. Lead author Darmofal may be reached at darmofal@mit.edu.

Aero-Astro Professor Mark Drela. “An awesome teacher and gifted engineer.” (William Litant photgraph)

Faculty Profile

MARK DRELA'S RESEARCH — AND HIS TEACHING — OFFER BEAUTY FROM FUNCTIONALITY

by Lauren Clark

World-renowned as an aerodynamicist, and human-powered vehicle expert, Professor Mark Drela is also admired by his colleagues and students as a superb (and fun) teacher.

In 1988, Daedalus, a lightweight aircraft designed by MIT Professor Mark Drela, set the world distance record for human-powered flight by traveling 72.4 miles from Crete to the Greek island of Santorini. That accomplishment put Drela on the map as a leading expert on human-powered flight. However, even more significant than the world record was the advance in computational aerodynamic design that went into building Daedalus. It ensured Drela would be recognized as one of the best aerodynamicists and airplane designers in the world.

To design and test Daedalus, Drela developed a software program called XFOIL. A kind of MATLAB for aerodynamicists, XFOIL wrapped established computational techniques for airfoil design in a graphical, intuitive interface. The program's ease of use and reliability enabled the Daedalus team to test and retest aircraft designs much more rapidly than previous, more cumbersome programming methods. Like MATLAB, XFOIL "does all the grungy details for you, so you can think more conceptually. And that really fits into how engineers do their job," says Drela.

MIT Professor Emeritus Jack Kerrebrock, a mentor during Drela's early days in the Department of Aeronautics and Astronautics, says that his colleague's designs for

Mark Drela's enthusiasm for aircraft design and flying model planes, is highly contagious, say his students. (William Litant photograph).

human-powered aircraft and watercraft "have the beauty that stems from perfect functionality, and they were executed at an extraordinary level of precision using design tools of his own development. The aerodynamic design tools that he has developed have set a new standard of accuracy and usefulness for the aeronautical industry and are widely used in the design of commercial and military aircraft and their engines."

Drela not only designs human-powered aircraft, but has also engineered aircraft for Boeing, the wing for the Predator UAV, the keel of America's Cup yachts, and experimental aircraft used by NASA. In addition to XFOIL, he has written design programs for rotorcraft, machinery blading, and axisymmetric bodies such as zeppelins. All of these programs have been "developed in actual use, by myself and other people," he says.

A ROLE-MODEL EDUCATOR

Department colleagues point admiringly to Drela's skill as an educator. "Mark is an awesome teacher and gifted engineer. His lectures and papers are laced with original insight and intellectual nuggets. He is *always available* — 24/7 — to help any student or participate in any undertaking. Mark is a role model for many of us who try to reach his level of excellence," says Department Deputy Head Earll Murman.

Drela came to MIT as a freshman in 1982 and went on to receive the SB, SM, and PhD in aeronautics and astronautics. "I was in aero since I was five years old," he laughs, recalling building his first model airplane in his native

Poland. He attended high school in the Philadelphia suburbs after his family emigrated to the U.S.

When he arrived at the Department, the field and its students were shifting focus from "hands-on, hardware stuff" to the computer- and information-science realm of aircraft engineering. Drela melded expertise in both areas to great effect by creating computer software that made aerodynamic design easier and faster.

Sitting in his office, surrounded by model aircraft he built, Drela describes XFOIL and similar programs he has written as "numerical wind tunnels. If you have a wing or an airfoil, and you need to find out how it does — what the drag is, what the lift is — you can actually compute it. It can be 1,000 times less expensive in terms of time and money to compute something on the computer instead of in a wind tunnel, which means that instead of testing one design you can test 1,000 designs. Nowadays, a freshman (using XFOIL on a desktop computer) can do the same work that required a team of computer operators 30 years ago. It's a huge change in capability."

After Daedalus made its unprecedented flight, Drela used XFOIL to design a new record-setting craft: the Decavitator, a human-powered hydrofoil that he pedaled to a world-record speed of 18.5 knots over a 100-meter race course on Boston's Charles River in 1991. Both Daedalus and Decavitator are on display at the Boston Museum of Science.

A FRESHMAN USING DRELA'S XFOIL ON A DESKTOP COMPUTER CAN DO THE WORK THAT REQUIRED A TEAM OF COMPUTER OPERATORS 30 YEARS AGO

Five years ago, Drela made XFOIL freely available on the Web under the General Public License. Since then, students, researchers, engineers, and aviation enthusiasts around the world have downloaded the program for both teaching and practice. XFOIL is used not only to design aircraft, says Drela, but also sailboats, propeller blades, windmills — "essentially any kind of lifting device that has air going over it."

FLYING NOODLES AND ASWING

A recent area of focus for Drela has been modeling very flexible airplanes. He consulted on an experimental unmanned aircraft called Helios, built by AeroVironment Inc. under NASA sponsorship. Intended as a sat-

In early April, Unified students organized a display of devotion to Professor Mark Drela by donning t-shirts bearing an alpha (angle of attack) on the front, and, on the back, a drawing of superhero Drela ripping open his shirt to reveal another alpha and the legend "Airdrela." (James Houghton photograph)

ellite substitute, the solar-powered craft flies in the thin upper atmosphere two to three times higher than a typical crusing jetliner. For this reason, it must be light and flexible. Nicknamed "the flying noodle," Helios is essentially a large, undulating wing with several small propellers.

"Designing an airplane like that is very hard, because you can't assume what the shape is," says Drela. "The shape depends on the air load and the air load depends on the shape. So you have this problem where you design the structure and the aerodynamics all at once."

To tackle the problem, Drela developed a nonlinear modeling program called ASWING. Whereas Helios engineers started out having to combine separate aerodynamic- and structural-analysis tools in an ad hoc way, ASWING "put these things together and made them easier to use and essentially solved the whole problem in an integrated fashion rather than piecemeal."

Drela plans to continue moving toward the design of vehicle systems rather than components. He is developing a design package that would enable rapid modeling and immediate flight simulation of an aircraft. “This prototyping system will fit well into the CDIO (conceive, design, implement, operate) structure of the Aero-Astro curriculum,” he says.

Drela teaches aircraft design fundamentals, external aerodynamics, and fluid mechanics of boundary layers to both undergraduate and graduate students. He notes how aero and astro students have shifted over the years from “mechanical types” who build model airplanes to those whose knowledge of aircraft has come almost purely from computer simulations. This poses a challenge to Drela as an instructor. “Doing stuff in software is fine, but ultimately, (aircraft modeling) has to be *done*.” He pats the PC on his desk. “Even a computer is made of something.”

Lauren Clark is a freelance writer and a communications assistant in the MIT School of Engineering Dean’s Office. She may be reached at ljclark@mit.edu

Aero-Astro alumna Janice Vos aboard the Space Shuttle Endeavour, mission STS-99, in February 2000. (NASA photograph)

Alumna Profile

SCI-FI TURNS HIGH-FLY FOR ASTRONAUT-ALUMNA JANICE VOSS

By Matthew Silver

In Madeleine L'Engle's science fiction novel, ***A Wrinkle in Time***, a high school girl embarks with her brother on an adventure through space and time to battle evil forces at nearby stars and rescue her father trapped on an alien planet. Among the millions of minds this story has captivated is that of a young Janice Voss who, years later as MIT Aero-Astro alum and an astronaut, brought a copy into space to later present the author.

Enthralled with spaceflight through science fiction and the world of the imagination, Janice Voss brought a focus and determination to her MIT studies and goals, which allowed her to bring the inspiration full circle. "I got into space exploration because of science fiction," says Voss. "Since high school I wanted to be an astronaut."

Selected for training in 1990 as the first female astronaut from MIT, Voss has blasted into space five times, traveling a total of 18.8 million miles in 779 orbits over 49 days. She is tied with Shannon Lucid, Bonnie Dunbar, and Tamara Jernigan for the record number of space flights by a woman. Of this achievement, she told MIT Tech Talk in 2000, "I don't think of it as a record, but a work in progress."

Her missions have included a rendezvous with the Mir Space Station; operating experiments in SpaceHab, the first commercial laboratory module in space; and mapping 47 million square miles of the Earth's surface. The latter activity, which took place on her fifth flight, resulted in a high-resolution digital elevation map of 80 percent of the earth's surface.

Voss oversaw numerous experiments over her five flights, including many designed to understand how animals and edible plants grow in space. She became adept at operating the Space Shuttle's robotic arm, deploying and retrieving satellites on her second mission in 1995. Voss was payload commander on her third flight in 1997, conducting experiments on micro-vibrations and combustion in micro-gravity.

AN ELEMENT OF DANGER

Like a good science fiction story, Voss's missions have not been without their element of danger. On her third flight, ground operators detected voltage irregularities in one of the Space Shuttle's three electricity-generating fuel cells. Fearing an explosion, they cut the mission to a "minimum duration flight," descending after five days instead of the planned 16. Was Voss worried? "Actually, I was on my sleep rotation when the problem was discovered," she says, "By the time I woke up the decision to move to minimum duration flight had been made."

> **"DURING THE EXTRA DAY IN ORBIT, I HAD TIME TO FLOAT BY THE WINDOW OF THE SPACE SHUTTLE AND READ...BY THE LIGHT OF THE EARTH. BEING IN SPACE READING SCIENCE FICTION BY EARTHLIGHT WAS AMAZING. IT FELT LIKE THINGS HAD COME FULL CIRCLE."**

While initially disappointed, the crew and the experiments flew again for a full 16 days a few months later, resulting in total space time permitting more science than would have been possible in the original mission.

All of Voss's flights were successful, and she has many fond memories. Among the most meaningful of her special moments occurred at the end of her first flight. Weather on Earth delayed descent by a day, giving Voss a chance to read in space the very stories that had inspired her career.

"I had brought Isaac Asimov's novel *Foundation* as one of my two personal items," Voss explains. "During the extra day in orbit, I had time to float by the window of the Space Shuttle and read it by the light of the Earth. Being in space reading science fiction by Earthlight was amazing. It felt like things had come full circle."

Originally from South Bend Indiana, Voss spent her high school days in Wilbraham, Massachusetts, where, she says, her love for science fiction turned into her goal to pursue a career in the space program. Voss received a Bachelor's in Engineering Science from Purdue in 1975.

AERO-ASTRO FOSTERS SKILLS, PLANNING

Voss entered MIT in 1976, where she learned both the skills and planning it would take to realize her dream. She completed a Master's in Electrical Engineering in 1978, writing a thesis on Kalman filtering techniques. The knowledge proved so useful that she eventually turned her thesis into a workbook for the astronaut corps.

For her Ph.D. in the Aero-Astro Department, Voss examined the guidance and control of large space structures, with particular attention to modal dynamics. As an astronaut, she notes, Dr. Richard Battin's course in astrodynamics (16.346) proved particularly handy.

In addition to academic knowledge she gained at MIT, Voss learned how to put her career goals into practice. "[Former] NASA astronaut Rusty Schweickart gave a talk while I was doing my masters, and made the point that it is very difficult to make it into the astronaut corps, so it is important to have a plan A and plan B." Plan A, of course, stood for Astronaut. Voss took this advice and, given her passion for space, Plan B involved working in space operations in some other capacity.

What is Voss's advice for today's aspiring astronauts? Having Plan A and Plan B is important, she councils. But, as importantly, "Do what you love. No one can predict what NASA will want in five or ten years, but one thing that is certain is that they will want excellence. Doing what you love will ensure that you will excel, and that will give you a better chance of being selected."

What is Voss' advice for aspiring astronauts?

"DOING WHAT YOU LOVE WILL ENSURE THAT YOU EXCEL."

It is also important to have a certain amount of breadth in addition to depth, Voss notes. This was partly her motivation for pursuing the masters in Electrical Engineering before concentrating on Aeronautics and Astronautics. "Many of the qualities that NASA looks for such as computer skills, being fit, or speaking with the public, are valuable in any field. These will help you move into other fields if you want to later."

For Voss, doing what she loved at MIT included spending long hours gorging herself on free science fiction at the MIT Science Fiction Society. A life-long dancer, she also participated in the Ballroom Dance Club and the MIT Tech Square-Dancers. In fact, on her last flight in space Voss participated with German astronaut and fellow dance-aficionado Gerhard Thiele in what may have been the first official ballroom dance in space. They danced the Swing.

“We quickly discovered it doesn’t work if both people are free-floating. And both people anchored would have been pointless.” Voss explains, “So we decided that the guy has to be anchored since he leads, but then you need a dance where the guy doesn’t move. The only ballroom dance like that is the Swing.”

These days Voss is no longer on flight status, which means she will not fly again. She works at the NASA Ames Research Center as the Science Director for the Kepler Spacecraft, scheduled to launch aboard a Delta II rocket in June, 2008. Kepler will look for Earth-sized planets around distant stars, focusing on orbital distances known as “habitable zones” where liquid water could be present. Results from the Kepler mission will give us a better idea of where our solar system fits within the continuum of solar systems throughout the galaxy.

The Kepler mission is a fitting continuation of Voss’s career in the space program, which began nearly 40 years ago when she read about adventures through space and time, to nearby stars surrounded by distant worlds and alien civilizations. With some luck, perhaps she will help turn yet another element of good science fiction into reality.

Matthew Silver is a researcher in the MIT Space Systems Laboratory and a freelance writer. He has master’s of science degrees from MIT in Aeronautics and Astronautics, and Technology and Policy. He can be reached at mrsilver@mit.edu

A Review of Aeronautics and Astronautics Department Research Laboratories

LAB REPORT

Information provided by the laboratories and research centers

AEROSPACE COMPUTATIONAL DESIGN LABORATORY

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

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

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

The creation of computational decision-aiding tools in support of the design process is the objective of a number of methodologies currently pursued in the lab. These include PDE-constrained optimization, real time simulation and optimization of systems governed by PDEs, multiscale optimization, model order reduction, geometry management, and fidelity management. ACDL is applying these methodologies to aircraft design and to the development of tools for assessing aviation environmental impact. ACDL faculty and staff include Jaime Peraire (director), David Darmofal, Mark Drela, Robert Haimes, Ngoc Cuong Nguyen, Per-Olof Persson, and KarenWillcox.

Visit the Aerospace Computational Design Lab at http://raphael.mit.edu/

AEROSPACE CONTROLS LABORATORY

The Aerospace Controls Laboratory is involved in research topics related to control design and synthesis for aircraft and spacecraft. Theoretical research is pursued in areas such as high-level decision making, estimation, navigation using GPS, robust control, optimal control, and model predictive control. Experimental and applied research is also a major part of ACL. The advanced unmanned aerial vehicle, rover, automobile, and satellite testbeds enable students to implement their algorithms in actual hardware and evaluate the proposed techniques.

ACL faculty are professors Jonathan How and Steven Hall.

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

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.

CSRL faculty include Nancy Leveson (director), Charles Coleman, Mary Cummings, Wesley Harris, and Paul Lagace.

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

GAS TURBINE LABORATORY

The MIT Gas Turbine Laboratory is the largest university laboratory of its kind, focusing on all aspects of advanced propulsion systems and turbomachinery. GTL's mission is to advance the state-of-the-art in gas turbines for power and propulsion. Several unique experimental facilities include a blowdown turbine, a blowdown compressor, a shock tube for reacting flow heat transfer analysis, facilities for designing, fabricating and testing micro heat engines, and a range of one-of-a-kind experimental diagnostics. GTL also has unique computational and theoretical modeling capabilities in the areas of gas turbine fluid mechanics, aircraft noise, emissions, heat transfer and robust design. Three examples of the lab's work are the development of Smart Engines, in particular active control of turbomachine instabilities; the Microengine Project, which involves extensive collaboration with the Department of Electrical Engineering and Computer Science — these are shirt-button sized high-power density gas turbine and rocket engines fabricated using silicon chip manufacturing technology; and the Silent Aircraft Initiative, an effort to dramatically reduce aircraft noise with the goal to transform commercial air transportation.

GTL participates in research topics related to short, mid and long-term problems and interacts with almost all of the major gas turbine manufacturers. Research support also comes from several Army, Navy, and Air Force agencies as well as from different NASA research centers.

Alan Epstein is the director of the lab. GTL faculty and research staff include David Darmofal, Mark Drela, Fredric Ehrich, Yifang Gong, Edward Greitzer, Gerald Guenette, Stuart Jacobson, Jack Kerrebrock, Carol Livermore, Ali Merchant, Manuel Martinez-Sanchez, James Paduano, Zoltan Spakovszky, Choon Tan, Ian Waitz, and Karen Willcox.

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

HUMANS AND AUTOMATION LABORATORY

Research in the Humans and Automation Laboratory, Aero-Astro's newest research 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 the central focus of HAL.

Current research projects include investigation of human understanding of complex optimization algorithms and visualization of cost (objective functions); collaborative human-computer decision making in time-pressured scenarios (for both individuals and teams), human supervisory control of multiple unmanned aerial vehicles, developing metrics for evaluating display complexity; the impact of multiple alarms on driver performance; and display design for autonomous formation flying.

In conjunction with Draper Laboratory, HAL has kicked-off the Lunar Access project. The objective of this program is to develop a baseline lunar landing system design to enable pinpoint "anywhere, anytime" landings. The long-term goal is to develop a lunar lander simulator to test the design. While Draper will concentrate on the guidance, navigation, and control problem, HAL will focus on the operator-in-the loop, designing the human-computer interface. Also, the project will conduct trade studies for including the human at different control points such as in the lander, from orbit, or remotely from Earth. Professors Dava Newman and Nicholas Roy will contribute to the lunar lander design effort.

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

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

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 new technologies

Global information systems are central to the future operation of international air transportation. Modern information technology systems of interest to ICAT include: global communication and positioning; international air traffic management; scheduling, dispatch and maintenance support; vehicle management; passenger information and communication; and real-time vehicle diagnostics.

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

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

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

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

The Laboratory for Information and Decision Systems is an interdepartmental research laboratory that began in 1939 as the Servomechanisms Laboratory, focused 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.

LIDS recently experienced significant growth. The laboratory moved to the Stata Center in April 2004, a dynamic new space that promotes increased interaction within the lab and with the larger community. Laboratory research volume is now more than $6.5 million, and the size of the faculty and student body has tripled in recent years. LIDS continues to host events, notably weekly colloquia that feature leading scholars from the laboratory's research areas. The 10th annual LIDS Student Conference took place in January 2005, showcasing current student work and including keynote speakers. These, and other events reflect LIDS' commitment to building a vibrant, interdisciplinary community.

In addition to a fulltime staff of faculty, support personnel, and graduate assistants, every year several scientists from around the globe visit LIDS to participate in its research program. Currently, 17 faculty members, 20 research staff members, and approximately 110 graduate students are associated with the laboratory.

Aero-Astro LIDS faculty are John Deyst, Daniel Hastings, Eytan Modiano, and Moe Win. The laboratory is directed by Vincent Chan.

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

LEAN AEROSPACE INITIATIVE

The Lean Aerospace Initiative is a continuously evolving learning and research community that brings together key aerospace stakeholders from industry, government, organized labor, and academia. A consortium-guided research program, headquartered in Aero-Astro, and working in close collaboration with the Sloan School of Management, LAI is managed under the auspices of the Center for Technology, Policy and Industrial Development, an MIT-wide interdisciplinary research center.

The Initiative was formally launched as the Lean Aircraft Initiative in 1993 when leaders from the U.S. Air Force, MIT, labor unions, and defense aerospace businesses forged a partnership to transform the U.S. aerospace industry, reinvigorate its workplace, and reinvest in America, using an overarching operational philosophy called "lean."

LAI is now in its fifth and most important phase, having moved beyond the transformation of business units toward that of entire enterprises. This will be accomplished through research, and the development and promulgation of practices, tools, and knowledge that enable enterprises to effectively, efficiently, and reliably create value in a complex and rapidly changing environment. The stated mission of LAI in this fifth phase is to "enable focused and accelerated transformation of complex enterprises through the collaborative engagement of all stakeholders to develop and institutionalize principles, processes, behaviors and tools for enterprise excellence."

LAI accelerates lean deployment through identified best practices, shared communication, common goals, and strategic and implementation tools honed from collaborative experience. LAI also promotes cooperation at all levels and facets of an enterprise, and, in the process, eliminates traditional barriers to improving industry and government teamwork.

The greatest benefits of lean are realized when the operating, technical, business, and administrative units of an aerospace entity all strive for across-the-board lean performance, thus transforming that entity into a total lean enterprise.

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

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

MAN VEHICLE LABORATORY

The Man Vehicle Laboratory optimizes human-vehicle system safety and effectiveness by improving understanding of human physiological and cognitive capabilities, and developing appropriate countermeasures and evidence-based engineering design criteria. Research is interdisciplinary, and uses techniques from manual and supervisory control, signal processing, estimation, sensory-motor physiology, sensory and cognitive psychology, biomechanics, human factor engineering, artificial intelligence, and biostatistics. MVL has flown experiments on Space Shuttle Spacelab missions and parabolic flights, and has several flight experiments in development for the International Space Station. NASA, the National Space Biomedical Institute, and the FAA-sponsored ground-based research. Projects focus on advanced space suit design and dynamics of astronaut motion, adaptation to rotating artificial gravity environments, spatial disorientation and navigation, teleoperation, design of aircraft and spacecraft displays and controls and cockpit human factors. Annual MVL MIT Independent Activities Period activities include ski safety research, and an introductory course on Boeing 767 systems and automation.

MVL faculty include Charles Oman (director), Jeffrey Hoffman Dava Newman, and Laurence Young,. They also teach subjects in human factors engineering, space systems engineering, space policy, flight simulation, space physiology, aerospace biomedical and life support engineering, and the physiology of human spatial orientation.

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

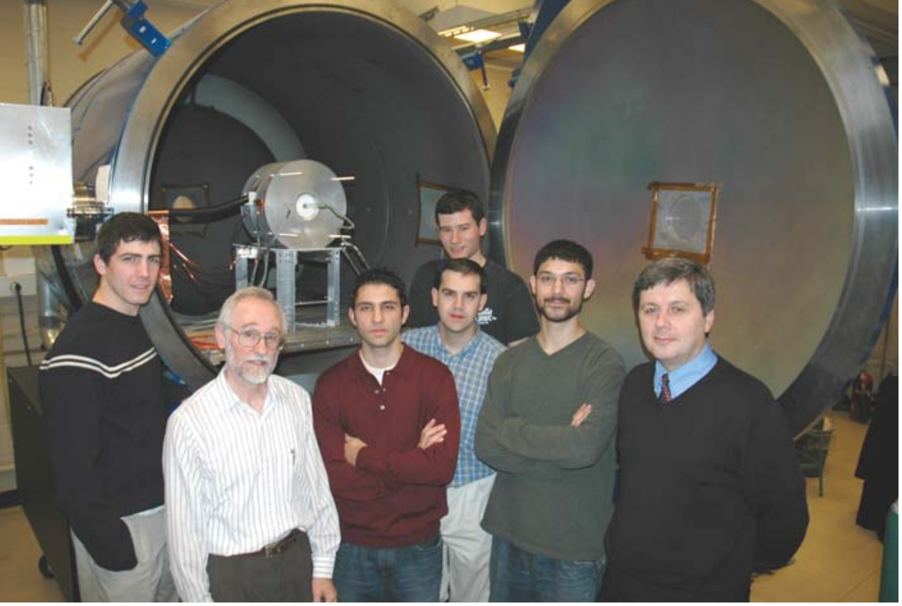
THE PARTNERSHIP FOR AIR TRANSPORTATION NOISE AND EMISSIONS REDUCTION

The Partnership for AiR Transportation Noise and Emissions Reduction is an MIT-led FAA/NASA/Transport Canada-sponsored Center of Excellence. PARTNER's goal is to be a world-class research organization closely aligned with national and international needs. PARTNER leverages a broad range of stakeholder capabilities, thereby fostering breakthrough technological, operational, policy, and workforce advances for the betterment of mobility, economy, national security, and the environment. PARTNER represents the combined talents of 10 universities, three federal agencies, and 50 advisory board members spanning a range of interests from local government, to industry, to citizens' community groups. Industry participants include General Electric, Pratt & Whitney, Rolls-Royce, Snecma, Boeing, Airbus, Bombardier, Bell Helicopter, Cessna, Delta Airlines, UPS, Gulfstream, Lockheed-Martin, Sikorsky, the Air Transport Association, Aerospace Industries Association, Airports Council International, and other smaller organizations.

Among major PARTNER projects are a landmark aviation and environment report to the U.S. Congress; testing alternate descent patterns to reduce aircraft landing noise, fuel consumption, and pollutant emissions; and development of simulations to assess policies, technologies and operational options for enabling environmentally responsible and economically viable air transportation growth.

PARTNER is directed by Aero-Astro Professor Ian Waitz. Other MIT participants include professors Peter Belobaba, Edward Greitzer, Henry Jacoby (Sloan School of Management), Karen Polenske (Urban Studies and Planning), Jack Kerrebrock, Karen Willcox, and Joel Cutcher-Gershenfeld (Sloan School of Management), as well as many research engineers, post docs, and graduate students.

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



In November 2005, a Space Propulsion Lab team achieved "first plasma" in its Helicon Wave plasma generator, a device for research into advanced forms of space thrusters. The team included (from left) senior Adam Shabshelowitz; SSL head Professor Manuel Martinez-Sanchez; graduate students Nareg Sinenian, Joe Palaia, sophomore Zachary LaBry (rear); and Justin Pucci; and Helicon project director Dr. Oleg Batishchev. (William Litant photgraph)

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 and important, 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.

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

SPACE SYSTEMS LABORATORY

The Space Systems Laboratory engages in cutting-edge research projects with the goal of directly contributing to the current and future exploration and development of space. SSL's mission is to explore innovative concepts for integration of and into future space systems, and to train a generation of researchers and engineers conversant in this field. General areas include developing the technologies and systems analyses associated with small spacecraft, precision optical systems, International Space Station experiments, and planetary exploration. The laboratory encompasses expertise in systems architecting, dynamics and control, thermal analysis, space power and propulsion, microelectromechanical systems, and software development. Major activities in the SSL are the development of formation flight technology testbeds and involvement in the NASA Concept Evaluation and Refinement (CE&R) study with the Charles Stark Draper Laboratory. The first of these activities has produced SPHERES, which will be launched to the International Space Station, EMFF, a system that uses electromagnets instead of thrusters for spacecraft formation control, and SWARM, a new demonstration of modular, wireless spacecraft docking and assembly. The CE&R study is focused on synthesizing and analyzing architectural options for future manned and robotic exploration of the Earth-Moon-Mars system, as well as real options analysis for Earth-to-Orbit launch and assembly. In addition, the SSL is developing technologies for interferometric space-based telescopes, low cost star trackers and mappers, stereographic imaging systems and space nuclear power and propulsion.

SSL faculty and research staff include David Miller (director), Ray Sedwick (associate director), Edmund Kong, John Keesee, Olivier de Weck, Ed Crawley, Daniel Hastings, Annalisa Weigel, Manuel Martinez-Sanchez, Jon How, Paul Bauer, and Paul Wooster.

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

TECHNOLOGY LABORATORY FOR ADVANCED MATERIALS AND STRUCTURES

An enthusiastic 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 hasten the exploitation of advanced materials systems in, and the use of, various advanced structural applications.

The laboratory has recently broadened its interests from a strong historical background in composite materials and the name change from the Technology Laboratory for Advanced Composites reflects this. The research interests and ongoing work thus represent a diverse and growing set of areas and associations. Areas of interest include:

- Nano-engineered hybrid advanced composite design, fabrication, and testing
- Composite tubular structural and laminate failures
- MEMS-scale mechanical energy harvesting modeling, design, and testing
- Durability testing of structural health monitoring systems
- Thermostructural design, manufacture, and testing of composite thin films and associated fundamental mechanical and microstructural characterization

- Continued efforts on addressing the roles of lengthscale in the failure of composite structures
- Further reengagement 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 specimens such as coupons, shafts, stiffened panels, and pressurized cylinders, made of composites, active, and other materials. TELAMS testing capabilities include a battery of servohydraulic machines for cyclic and static testing, a unit for the catastrophic burst testing of pressure vessels, and an impact testing facility. TELAMS maintain capabilities for environmental conditioning, testing at low and high temperature, and in general and hostile environments. There are facilities for microscopic inspection, for high-fidelity characterization of MEMS structures and devices, and a laser vibrometer for mechanical and electrical testing of electromechanical materials and devices.

With its ongoing, linked and coordinated internal and external efforts, the laboratory has renewed its commitment to leadership in the advancement of the knowledge and capabilities of the composites and structures community through education of students, original research, and interactions with the community. There has been a broadening of this commitment consistent with the broadening of the interest areas in the laboratory. In 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.

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

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

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 new 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, astronauts' 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 more than a half century of operations, Wright Brothers Wind Tunnel work has been recorded in several hundred 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

An appreciation

GENE COVERT AND THE GUGGENHEIM MEDAL

For 60 years, he's swung at every career pitch, and hit most out of the park

By William T.G. Litant

It was in 1946 that the Bell 47 was awarded the first commercial helicopter license, the WAC became the first American rocket to leave the atmosphere, TWA inaugurated international flights, and the Douglas B-43 flew as the first American jet bomber. It was that same year that 20-year-old Eugene Covert started work at the Naval Air Modification Unit's Pilotless Aircraft Division on projects that would result in the Sparrow, the West's famed primary air-to-air missile from the 1950s through the 1990s.

Gene Covert accepts congratulations from MIT President Susan Hockfield for his receipt of the Guggenheim medal. (William Litant photograph)

Six decades later, MIT Aeronautics and Astronautics Professor Emeritus Covert's accomplishments and honors are legendary. He's a Fellow and an Honorary Fellow of several learned societies, and is member of the National Academy of Engineering. He's the recipient of numerous awards, including the AGARD Von Karman Medal, the AIAA Ground Testing Award, AIAA Durand Lectureship, U.S. Air Force Exceptional Civilian Service Medal, and University Educator of the Year.

And now, his career has been capped with one of the most prestigious awards in aviation: the Daniel Guggenheim Medal. Jointly sponsored by the American Institute for Aeronautics and Astronautics, American Society of Mechanical Engineering, the American Helicopter Society, and the Society of Automotive Engineers, the medal recognizes those who have made profound contributions to advancing aeronautics. Targeting Covert for the big gold disk that bears the image of the Spirit of St. Louis, the Guggenheim committee cited his "exemplary leadership in aeronautics teaching and research, development of significant state-of-the-art aerodynamic testing techniques, and outstanding contributions to public service."

In the spring of 2006, a business-suited Covert tips slightly back in his office chair, hands folded in his lap, staring over a visitor's shoulder, pondering his years in aerospace. "My career was a set of building blocks," he says. "I learned something every step along the way." He says many of the steps "broadened," and some were "broken"—but he gained in knowledge from every one.

Covert's career spanned research and teaching, to public service. In the 1950s, he conducted tests on numerous aircraft, including the famed F-4 Phantom, at the MIT Naval Supersonic Wind Tunnel. His interest in the problems of supporting models led him to develop the world's first practical wind tunnel magnetic suspension system.

Professor Eugene Covert discusses graduate student advisee USAF Lt. John Keesee's research in 1974. (MIT Museum photograph)

"Gene's contributions to aerospace research, education, and public service are equally profound and we're thrilled he's been honored with the Guggenheim — this highest form of recognition," says Aero-Astro head Wesley Harris. "The entire Aero-Astro department celebrates with him."

From 1972-73, Covert was chief scientist of the U.S. Air Force. The following year, he was back at MIT where one of his graduate advisees was 23-year-old Air Force Lt. John Keesee. Retired last year as a full colonel, Keesee is now an Aero-Astro lecturer who fondly recalls his advisor. "He was extremely highly regarded by the Air Force and DOD," Keesee says. "If they had an issue with aerodynamics, he was the person they'd call. He'd come back from a trip and say to me, 'I was in Washington working for *your* Air Force.'" Keesee chuckles when he recalls Covert's role as his advisor. "He was always O.K. letting you do whatever project interested you, even if it was kind of dumb. He'd let you do it — and then he'd let you redo it." Trying things, whether they are destined to work or not, is an important Covert philosophy he's applied to his own life. "It was like being in a batting cage," Covert muses. "I missed a fair fraction, but I took a swing at everything."

From 1978-79, Covert was technical director of the European Office of Aerospace Research and Development. Later, he was a NASA consultant on the Space Shuttle main engine, and was a member of the commission that examined the Challenger accident. He was appointed to the MIT faculty in 1963, and was Aero-Astro department head from 1985 until 1990.

When Covert learned *Aero-Astro* was preparing a tribute to him in these pages, he insisted it include a salute to his wife, Mary Rutford Covert, and family. "I could have only accomplished what I did by having a supportive wife and family. Their contribution (to my success) was as great as any. It's important that that gets in."

He also specified another comment. "In the course of my career I have had the opportunity to visit many places in the United States and throughout the world, including the South Pole, where I have met many very friendly, intelligent, and interesting people. The exception was the North Pole where we had to bring our own people." Gene is also known for his sense of humor.

No one is a more appropriate recipient of the great Guggenheim Medal. For 60 years, students, faculty, academic leaders, engineers, policymakers, government agencies, professional associations — indeed, the entire breadth and range of the aerospace community — have been the fortunate benefactors of Gene Covert's expertise, professionalism, insight, and wit. He is a treasure, and we at MIT are fortunate that we've had a good share of him — and expect to do so for the foreseeable future. Gene: congratulations on this magnificent, well-deserved honor.