

# AEROASTRO

annual 2006-2007



MASSACHUSETTS INSTITUTE OF TECHNOLOGY

## **AERO-ASTRO**

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## **DESIGN**

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Cover: Graduate students Brett Bethke (left) and Mario Valenti watch as a quadrotor flying  
vehicle they helped develop autonomously makes its way about the Aeronautics and Astronautics  
Department's Aerospace Controls Lab. (Donna Coveney/MIT photograph)

Dear colleagues and friends:

Welcome to Aero-Astro, the MIT Department of Aeronautics and Astronautics' annual report about the people, research, and educational activities in our community. While we on campus continually witness the Department's advancements in research and learning, reviewing the submissions to this publication impresses us each time we do it.

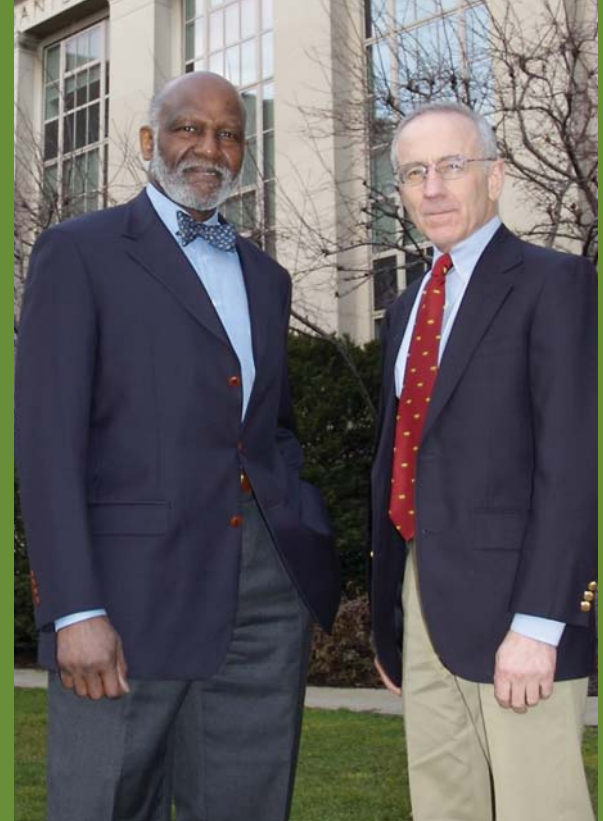
In this issue you will read about a combined Cambridge University-MIT project to develop the conceptual design of a "silent aircraft," ground-breaking research in autonomous unmanned aerial vehicle operation, application of conceive-design-implement-operate hands-on learning in Aero-Astro courses, and about some wonderful volunteer and engineering work three of our students are doing to improve the lives of others. You will also see profiles of alumnus Brad Parkinson, a recipient of the National Academy of Engineering's Draper Prize (sometimes referred to as the Nobel Prize for Engineering), and Professor of the Practice Bob Liebeck, who is manager of Boeing Phantom Works Blended Wing Body aircraft project and a Boeing Technical Fellow.

A brief look of some of the other happenings in the Department over the past year:

- Three outstanding junior faculty members joined the Department. Hamsa Balakrishnan, who comes to us from Stanford via NASA Ames, specializes in air traffic control, traffic flow management, airport operations scheduling, and hybrid systems. Emilio Frazzoli, who gained his Ph.D. at MIT, and has been an assistant professor at UCLA, has expertise in aerospace control systems, autonomous air/space/ground vehicles, mobile robotics, systems and control theory, optimization algorithms, real-time and embedded systems. Paulo Lozano, the Charles Stark Draper Assistant Professor of Aeronautics and Astronautics, an MIT Ph.D. and a former research scientist with this department, has interests in electric propulsion, electrosprays, thruster physics, electrochemical microfabrication, engine health monitoring, and space mission design.

- With generous support from Dean Magnanti, we are developing two new initiatives. One of these is focused on UAVs (such as the one on the front cover). The other addresses the engineering of small satellites. The hope is that both of these will grow into major projects that involve multiple faculty members.
- Our undergraduate enrollment remained strong: 62 sophomores, 60 juniors, and 61 seniors. And, as we go to press, we expect to produce 28 doctorates by June, the highest number in the past five years.
- The Department shared the top ranking (with Stanford and Caltech) in the recent U. S. News and World Report listings of graduate schools.
- Our research is generating interest and excitement around the world. We don't have the space to cover all this work, but we offer some examples. Dave Darmofal and his students have developed an adaptive finite-element method for aerodynamics and are collaborating with Boeing and NASA to apply the method to the design of supersonic aircraft. Nancy Leveson's Complex Systems Research Lab is doing landmark work with system modeling, analysis, and visualization theory and tools to assist in the creation of safer systems with greater capability. Dave Miller's SPHEREs microsats are undergoing rigorous testing aboard the International Space Station. Jaime Peraire's Aerospace Computational Design Laboratory is producing novel computational techniques for advanced simulation. Ian Waitz's Partnership for AiR Transportation Noise and Emissions Reduction research collaborative is developing tools to assess the costs and benefits of strategies to provide for policy-makers who must address aviation's environmental impact. Jon How's advancements in autonomous multivehicle operation are bringing us closer to the day when formations of UAVs will serve for border security, military convoy protection, and a host of other applications enhancing our safety and security. And, Karen Willcox's reduced-order modeling will offer researchers powerful new techniques for the creation of small, yet accurate models of complicated systems.

We continue to face challenges such as changes in federal funding portfolios, growing environmental concerns about aviation, and evolution of our students' demographics and interests, and we look forward to meeting these with the unparalleled expertise, enthusiasm, and energy of our greatest asset — the people of Aero-Astro.



Wesley Harris (left) and Edward Greitzer

Wesley Harris  
Department Head

Edward Greitzer  
Deputy Department Head

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While originally conceived to make a substantial reduction in airplane noise, the MIT-Cambridge University silent aircraft design could achieve 124 passenger-miles per gallon, almost 25 percent more than current aircraft. Aimed at the 2030 time frame, some of the quiet technologies the MIT-Cambridge team developed could be incorporated sooner.

# THE SILENT AIRCRAFT

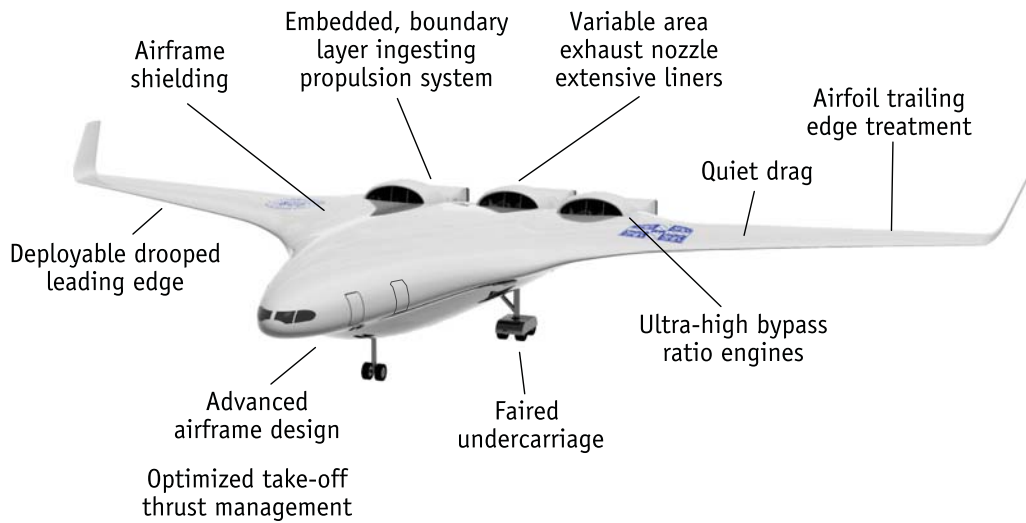
By Ann Dowling, Edward Greitzer,  
Thomas Hynes, James Hileman,  
and Zoltan Spakovszky

Aircraft noise is recognized as a major barrier in the expansion of airport operations. While there has been progress in aircraft noise reduction, further reductions become harder to achieve. The problem is made more difficult by the anticipated increase in noise due to the growth in aircraft operations. Greener by Design, a UK working group that seeks “solutions to the challenge posed by aviation’s impact on the environment,” has stated: “the downward trend in noise exposure around airports of past years ... has now flattened out at major airports. Virtually all the older aircraft have been phased out and, while the continued fleet renewal will introduce progressively quieter types, the benefit will be appreciably less than has been achieved from phasing out of (older, noisier) aircraft.”

was the conceptual “Silent Aircraft eXperimental” design SAX-40. The aircraft has an estimated noise level less than the background noise of a well-populated area and a predicted 23% fuel burn reduction compared to current civil aircraft.

SAI aimed to take a major step beyond aviation industry’s noise reduction targets, a target that would call for a highly integrated airframe and engines, as well as operations and design co-optimized for low noise. This ambitious goal would necessitate involving a range of partners from academia, industry, and government; a collaboration among organizations and individuals with different skills and interests. For example, the project would include

The Silent Aircraft Initiative was created to meet the challenge of further reducing aircraft noise the in face of ever-increasing aircraft operations. The approach was to make radical reduction in noise a primary design criterion. The project goal was to design an aircraft quiet enough to be imperceptible to people in the urban environment around airports while being competitive with existing and next generation aircraft fuel burn and emissions. A key project outcome



The silent aircraft is designed to carry 215 passengers with a range of 5000 nautical miles at a cruise of Mach 0.8. The conceptual design airframe differs radically from current civil aircraft. There are conventional supercritical wings, but the fuselage is a lifting body, aerodynamically shaped to achieve enhanced low speed and cruise performance without the need for conventional flaps and a tail. The wingspan is 222 feet (67.5 m) including the winglet, maximum takeoff weight is 332,000 lbs (151,000 kg).

research into airframe and engine design, and ways to reduce noise by changing takeoff and approach procedures. There would be an economic assessment of regulatory scenarios under which the aircraft would present an attractive business case to an airline, and an estimate of national and local economic benefits.

SAI is one of the Cambridge (University)-MIT Institute's Knowledge Integration Communities (KICs); research communities exploring ways for academia, industry, and government to work together. The KIC fosters linkages and two-way flows of information between academic researchers and their colleagues in commerce, enhancing the impact of the research. The SAI community comprised airframers, engine manufacturers, airport and airline operators, air traffic controllers, regulators, and measurement specialists; more than 30 partners, in addition to the academics.



## DESIGN FEATURES

We designed for an aircraft mission of 215 passengers with a range of 5000 nm at a cruise Mach number of 0.8. The conceptual design's airframe differs radically from current civil aircraft. There are conventional supercritical wings, but the fuselage is a lifting body, aerodynamically shaped to achieve enhanced low speed and cruise performance without the need for flaps and a tail. The design parameter Mach number times lift/drag ratio is 20; for reference the Boeing Phantom Works Blended Wing Body has 17-18. The wing span is 222 feet (67.5 m) including the winglet, and the maximum takeoff weight is 332,000 lbs (151,000 kg).

The aircraft is propelled by a distributed high bypass ratio propulsion system (cruise bypass ratio of 12) embedded in the fuselage. There are nine geared fans driven by three gas generators. Each inlet feeds air to one engine cluster comprised of a turbofan and two auxiliary fans.

For the concept aircraft the community noise levels are estimated not to exceed 63 dBA for typical missions, comparable to the background noise in urban daytime environments. A substantial reduction (75 dB in cumulative Effective Perceived Noise for sideline, takeoff, and approach) is estimated relative to the current International Civil Aviation Organization noise standard.

There is a major fuel efficiency improvement predicted relative to current civil aircraft: 124 passenger-miles per (US) gallon compared to 101 passenger-miles per gallon for a Boeing 777, a 23% increase. For reference, the Toyota Prius hybrid car carrying two passengers is reported as having a city-highway fuel burn of 96 passenger-miles per gallon. It is expected that further fuel efficiency, even with respect to this major saving, could be achieved in an aircraft design specifically targeted to minimize fuel consumption and emissions.

**FOR THE CONCEPT AIRCRAFT THE COMMUNITY NOISE LEVELS ARE ESTIMATED NOT TO EXCEED 63 DBA FOR TYPICAL MISSIONS, COMPARABLE TO THE BACKGROUND NOISE IN URBAN DAYTIME ENVIRONMENTS.**

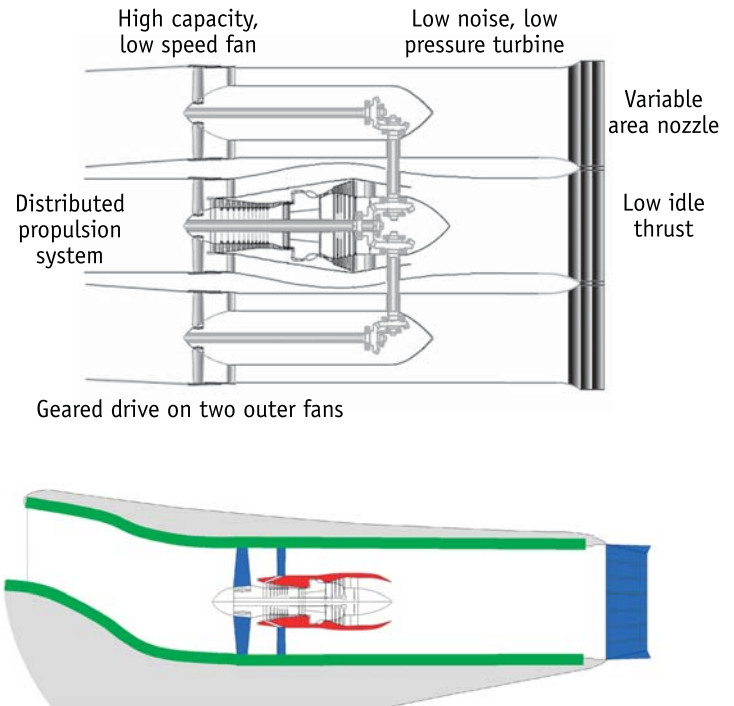
## NOISE REDUCTION TECHNOLOGIES

Low noise is not achieved by a single design feature. It results from many disciplines integrated into the design and operation of a noise-minimizing aircraft system. Many of these design features also reduce fuel burn and emissions.

The rationale for use of these features of the aircraft and the propulsion system can be summarized as follows:

- *Low noise approach operations:* On approach, the airframe generates half the noise and the noise sources strongly scale with the flight velocity. Substantial noise reductions can thus be achieved by using a low speed approach and a displaced runway threshold on landing, thereby increasing distance to listeners on the ground.
- *Efficient airframe centerbody design:* The leading edge region of the centerbody is aerodynamically shaped to balance aerodynamic moments for pitch trim and to provide static stability without a tail. At cruise conditions, the all-lifting airframe is calculated to achieve an elliptical span load distribution, improving the Mach number times lift/drag ratio parameter by 15% compared to current blended-wing body type aircraft designs. The enhanced low speed airframe performance allows stall speed reduction by 25% compared to current aircraft of similar size.
- *Airfoil trailing edge treatment:* Trailing edge brushes have been found to reduce the scattering noise from turbulence near the trailing edges. The estimated trailing edge noise reduction is 4 dBA.
- *Faired undercarriage:* The undercarriage noise sources can be mitigated by partially enclosing wheels and axles. Estimated noise reduction from use of fairings is roughly 6 dBA.

- *Deployable, drooped leading edge:* A deployable drooped leading edge can provide the required lift during low speed operations without the use of slats, thus eliminating slat noise. The drooped leading edge is stowed at cruise. Deployment power levels are comparable to a conventional slat. The Airbus A380 uses this configuration.
- *Quiet drag (needed on approach) via increased induced drag:* Large wing area and high angle of attack provide the lift at low speed without using deployable flaps, eliminating a major source of airframe noise on takeoff and landing. A combination of elevons and thrust vectoring can increase the induced drag to the required level, while trimming the aircraft.
- *Embedded, aircraft boundary layer ingesting, distributed propulsion system:* Ingestion of fuselage boundary layer air into the engine allows a potential reduced fuel burn. There is a trade between this gain and the losses due to the increased duct length needed for noise attenuation. Embedding the engines within the airframe implies a high degree of airframe and engine integration. Engine airflow is now affected by the airframe and, similarly, the presence of the engines alters the flow around the aircraft. There are several major challenges, associated with the non-uniform flow into the engine (distortion), which must be addressed for a practical aircraft configuration.



The silent aircraft is propelled by a distributed high bypass ratio propulsion system (cruise bypass ratio of 12). Unlike most civil aircraft today, which have their engines mounted externally, the silent aircraft's engines are embedded in the fuselage. There are nine geared fans driven by three gas generators. Each inlet feeds air to one engine cluster comprising a turbofan and two auxiliary fans. The top image shows a top view of the engines, indicating the gearing for the cluster (of three fans — one engine) that sits in each of the three intakes. The bottom image is a side view of the engine in the duct, to illustrate the length of duct available for acoustic liners. Overall conceptual design is aimed at the 2030 time frame, but part of the project strategy is that some of the quiet technologies the team developed could be incorporated nearer term.

- *Variable area exhaust nozzle to permit ultra-high bypass ratio, low fan pressure ratio, engines:* To reduce the engine noise at takeoff the engine exhaust velocity must be decreased. To ensure fan operability at the low power needed for low exhaust velocity the exhaust nozzle is designed to have variable area, with takeoff bypass ratio of 18, and cruise bypass ratio of 12. The low engine rotational speed during approach enabled by the variable nozzle reduces the rearward fan noise and the airframe drag requirements. The fan design, however, must now accommodate the broad range of flows associated with operation of low pressure ratio fans at different flight conditions.
- *Airframe shielding of engine noise:* Placing the engines above the airframe prevents engine noise from reaching the observer. Engine forward radiated noise is virtually eradicated on the ground.
- *Optimized takeoff thrust management:* Thrust, climb angle, and nozzle area would be continuously varied during takeoff to maintain a set noise level outside the airport boundary. This would allow the specified noise level to be met at all times during departure.
- *Optimized extensive liners:* The embedded propulsion system allows smaller engine diameter and thus increased non-dimensional (length/diameter) duct length. The longer inlet and exit ducts provide scope to further reduce engine noise by allowing additional acoustic liners, compared to conventional nacelles, to absorb the engine noise. In the design configuration, use of an optimized multi-segment liner results in an estimated 20 dBA reduction of engine noise.

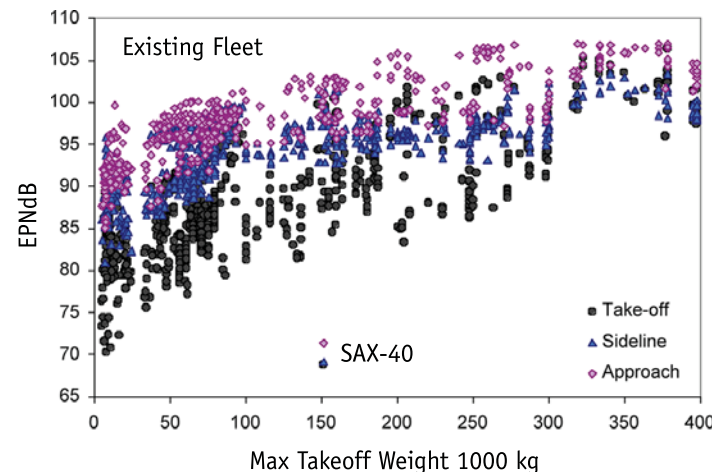
**SAI HAS BEEN AN INSTRUCTIVE AND USEFUL EXPERIMENT IN ACADEMIC-INDUSTRY INTERACTIONS, FROM STRATEGIC PLANNING AND DECISIONS TO DETAILED WORKING LEVEL TECHNICAL INTERCHANGE.**

## THE COLLABORATIVE PROCESS

A range of skills and interests beyond those of the two universities was needed to tackle the many challenges, necessitating a collaboration that included regulators, airport operators, airlines, aerospace manufacturers and representatives of community groups. SAI has been an instructive and useful experiment in academic-industry interactions on several levels — from strategic planning and decisions (input from the KIC members had a direct impact on the project goals) to detailed working level technical interchange.

Formal meetings of all the partners in the Knowledge Integration Community occurred at roughly eight-month intervals, but interaction with some partners was more frequent. Industrial partners gave the academic researchers access to some of their in-house design codes. Boeing, Rolls-Royce, NASA, and ITP conducted reviews and provided feedback on the designs. For example, Boeing made available its Multidisciplinary Design Optimization code, WingMOD, which optimizes the aircraft planform for a given mission. Rolls-Royce allowed use of the company's design, performance, and noise evaluation tools to examine concepts for new engine designs.

An academic team project that is carried out as part of student degree programs contains a set of goals that creates a tension in the overall conduct of the project. Each student needs to develop the new ideas that comprise his or her thesis in order to get their degree, and these need to be visible as a contribution that the particular student has made. However, there is also a need for the research results to be integrated into a workable design concept. There must thus be a clear, mutual,



This chart compares the effective perceived noise level of current commercial aircraft with the dramatically lower level for the SAX-40 (silent aircraft). For the SAX-40, the community noise levels are estimated not to exceed 63 dBA for typical missions, which is comparable to the background noise in urban daytime environments.

and explicit understanding by the advisor and student as to what the expected intellectual contribution for the thesis will be and how it will be consistent with participation in the overall design.

**THERE MUST BE A CLEAR, MUTUAL, AND EXPLICIT UNDERSTANDING BY THE ADVISOR AND STUDENT AS TO WHAT THE EXPECTED INTELLECTUAL CONTRIBUTION FOR THE THESIS WILL BE AND HOW IT WILL BE CONSISTENT WITH PARTICIPATION IN THE OVERALL DESIGN.**

Beyond the above discussions, however, processes were needed to ensure productive collaboration of the large research group as an integrated product team. This implies a vital need for effective communication and information exchange and the ability to make strategic decisions, sometimes based on limited available information. Weekly video conferences, and even more frequent email and telephone contact, were essential for the former aspect of the design integration, but, in industry, a chief engineer would deal with the latter type of issues. As the different pieces of the research started to come together and progress was made on the component designs, it became evident that such a function would also be of great value on the project. A faculty member and a post doctoral associate were assigned, and shared effectively, the role of co-chief engineers.

Finally, there were issues for which team members formed ad hoc task forces to address design decisions at crucial stages of the project. Examples of specific questions addressed in this manner are “What should be the design range?” and “Should the engines be podded or embedded?” The task forces were several week-long focused activities, drawing on members from all the relevant aspects of the research and involving exchanges of personnel. This last element helped to build the working relationships and also defuse “we-they” perspectives.

While collaboration was essential throughout the project, it was perhaps most critical in the area of aircraft operations, in which the team in Operations worked to develop an advanced form of Continuous Descent Arrival for current aircraft. CDA is a procedure enabling aircraft to make a single continuous descent from altitude to landing, rather than

the current procedure which involves a series of descent “steps.” It reduces noise levels on the ground along the approach path while also reducing fuel burn. Putting the new procedures in place was a many-step task that required agreements among air traffic controllers, regulators, suppliers, airport operators, and airlines; it is an example of something that could not have been achieved without this type of partnership.

In summary, the silent aircraft project brought industry, academia, and other stakeholders together around a “grand challenge” which captured the enthusiasm and imagination of all those involved. The Knowledge Integration Community includes industry, government, and academia, and provides an exciting way to address problems with a large reach, underpinning the vital nature of collaboration in achieving the potential for step-change improvements. As well as the conceptual design of a new type of aircraft, some of the technologies developed could be introduced into more incremental aircraft and engine designs. Collaboration and teaming occurred in basically all aspects of the project and, because of this, SAI has been very much an enterprise in which the whole is greater than the sum of the separate parts.

Dame Ann Dowling is Professor and Head of Division in the Cambridge University Engineering Department and was the Cambridge lead for the silent aircraft project. Edward Greitzer is the H. N. Slater Professor and Deputy Department Head of the MIT Aeronautics and Astronautics Department and was the MIT lead. Thomas Hynes is a Senior Lecturer in the Cambridge University Engineering Department and was head of the engine team. James Hileman and Zoltan Spakovszky are a Research Engineer and Associate Professor, respectively, in the Aero-Astro Department, and were the two project co-Chief Engineers.

**PUTTING THE NEW PROCEDURES IN PLACE WAS A MANY-STEP TASK THAT REQUIRED AGREEMENTS AMONG AIR TRAFFIC CONTROLLERS, REGULATORS, SUPPLIERS, AIRPORT OPERATORS, AND AIRLINES; IT IS AN EXAMPLE OF SOMETHING THAT COULD NOT HAVE BEEN ACHIEVED WITHOUT THIS TYPE OF PARTNERSHIP.**

MoRETA (Modular Rover for Extreme Terrain Access), a legged interplanetary rover that can access terrain too extreme for current rovers, is the current project of Professor David Miller's 16.832 Space Systems Product Development class. The CDIO capstone course, 16.832 presents students with the opportunity to apply all aspects of the conceive-design-implement-operate skills they've learned in Aero-Astro. (William Litant photograph)





# Conceiving, Designing, Implementing, and Operating CDIO IN AERO-ASTRO, AND BEYOND

By Edward F. Crawley

The CDIO Initiative is an innovative educational framework for producing the next generation of engineers. Developed initially in MIT Aero-Astro, CDIO provides students with an education stressing engineering fundamentals set in the context of Conceiving — Designing — Implementing — Operating real-world systems and products.

The CDIO Initiative was developed with input from academics, industry, engineers, and students. It is universally adaptable for all engineering schools. Twenty-four collaborating schools throughout the world have adopted CDIO as the framework of their curricular planning and outcome-based assessment.

Over the last decade, MIT, and, more specifically, the Department of Aeronautics and Astronautics, have been among the leaders in the ongoing reform of engineering education. In the Department, our specific contribution has focused on the CDIO program. The motivation, origins and evolution of the program, as well as a small hint at the valuable contributions made by our faculty, staff, and students, will be described briefly below.

The motivation for CDIO can be found by examining what engineers do. Aerospace engineers build and operate things that serve society — aircraft, airports, air transport systems and space launch and space-based systems. Theodore von Kármán said “Scientists discover the world that exists; engineers create the world that never was.” Modern engineers lead, or are involved in, all phases of an aerospace system life cycle; they Conceive, Design, Implement, and Operate.

The aim of the CDIO program, which takes its name from this life cycle view, is to do a better job at preparing engineering students for this future, by systematically reforming engineering education. We believe that every graduating engineer should be able to:

*Conceive-Design-Implement-Operate  
complex value-added engineering products, processes, and systems  
in a modern, team-based environment*

More simply, we must educate engineers who can engineer. For alumni educated before roughly the mid 1950s, this is a familiar theme — education in that era was founded largely on practice. By the 1980s, the adoption of the engineering science model of education, which had been intended to enrich the theme of practice, in fact largely displaced the skills of practice from our curriculum. Therefore, the CDIO Initiative has three overall goals intended to strike the appropriate balance among fundamentals, skills and technology. The goals are:

*To educate students who are able to:*

- 1. Master a deeper working knowledge of technical fundamentals*
- 2. Lead in the creation and operation of new products, processes, and systems*
- 3. Understand the importance and strategic impact of research and technological development on society*

A CDIO-based education always begins by emphasizing the technical fundamentals. University is the place where the foundations of subsequent learning are built. Nothing in a CDIO program is meant to diminish the importance of the fundamentals, or students' need to learn them. In fact, deep working knowledge and conceptual understanding is emphasized to strengthen the learning of technical fundamentals.

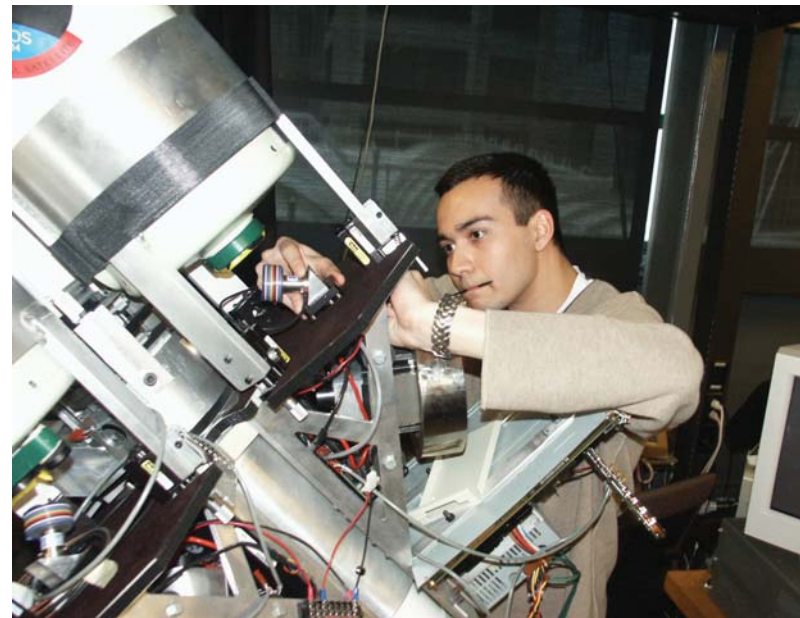
The second goal is to educate students who are able to lead in the creation and operation of new products, processes, and systems. This goal recognizes the need to prepare students for a career in engineering. The need to create and operate new products, processes, and systems drives the educational goals related to personal and interpersonal skills; and product, process, and system building skills.

The third goal is to educate students who are able to understand the importance and strategic impact of research and technological development on society. Our societies rely on the contributions of scientists and engineers to solve problems, ranging from healthcare to entertainment, and to ensure the competitiveness of nations. However, research and technological development must be paired with social responsibility and a move toward sustainable technologies.

### CDIO'S ORIGINS

In the 1990s, the Aero-Astro Department conducted two systematic strategic planning exercises. Both of these, but especially the later one in 1997, identified a deep concern with university based engineering education, and therefore opportunities for improvement. Industry consistently stated that while students emerge from universities like MIT with an excellent knowledge base, they lack the “skills,” such as teamwork, critical thinking, and social awareness, to effectively apply this knowledge to the development of new systems. This concern was reflected, for example, in the accreditation standards for engineering — ABET 2000. Our alumni voiced a similar view in surveys. They reported that the discipline base of their MIT education served them well, but increasingly in their career the generic, professional skills were more important. The Department heard this “voice of the customer” input very clearly.

Student Abran Alaniz makes adjustments to ARGOS, a multi-aperture design for a next-generation space telescope that was an Aero-Astro CDIO capstone project of several years ago. Projects like ARGOS provide excellent support for CDIO's emphasis on acumen with all stages of product development. (William Litant photograph)



At the same time, more bottom-up influence was being felt due to the long-standing commitment of the Department to quality in undergraduate education. Many of our faculty members, individually and in small groups, were experimenting with innovation in education. They were attempting to apply in practice the emerging scholarship on engineering education. The confluence of the interests of industry and alumni on one hand, and the commitment of our faculty and emerging research on education on the other, led to the establishment of CDIO as a goal of our strategic plan. We started a small pilot in the 1999-2000 academic year, and soon realized that resources and partners would greatly accelerate our effort.

**WE ENVISION AN EDUCATION THAT STRESSES THE FUNDAMENTALS, SET IN THE CONTEXT OF CONCEIVING-DESIGNING-IMPLEMENTING-OPERATING PRODUCTS, PROCESSES, AND SYSTEMS.**

In October 2000, MIT and three Swedish universities, Chalmers University of Technology, the Royal Technical University (KTH), and Linköping University, formally launched the CDIO Initiative. This was made possible through funding by many MIT alumni, corporations, and foundations, particularly the Knut and Alice Wallenberg Foundation of Sweden. This reform effort has now expanded to schools worldwide.

#### **THE CDIO VISION**

Underlying the CDIO approach are three key ideas: the context of the education; the “what” of the education, educational goals, and learning outcomes for the students; and the “how” of the education, a comprehensive approach to improving teaching and learning.

The first key idea is that we envision an education that stresses the fundamentals, set in the context of Conceiving-Designing-Implementing-Operating products, processes, and systems. The product, process, and system life cycle is considered the context for engineering education in that it is the cultural framework, or environment, in which technical knowledge and other skills are taught, practiced, and learned.

It is important to note that we assert that the product or system life cycle should be the context, not the content, of the engineering education. Not every engineer should specialize in product development. Rather, engineers should be educated in disciplines; that is, mechanical, electrical, chemical, or even engineering science. However, they should be educated in those disciplines in a context that will give them the skills and attitudes to design and implement things.

The rationale for adopting the principle that the system life cycle is the appropriate context for engineering education is supported by simple logic. It is what engineers do. It is the underlying need and basis for the skills lists that industry proposes to university educators. It is the natural context in which to teach these skills to engineering students.

The second key idea is that a CDIO education should be based on clearly articulated program goals and student learning outcomes, set through stakeholder involvement. The knowledge, skills, and attitudes intended as a result of engineering education; that is, the learning outcomes, are codified in the CDIO Syllabus, an early output of the CDIO Initiative (now translated into Swedish, French, Chinese, and Spanish). These personal, interpersonal, and system building learning outcomes detail what students should know and be able to do at the conclusion of their engineering programs. Personal learning outcomes focus on individual cognitive and affective development; for example, engineering reasoning and problem solving, experimentation and knowledge discovery, system thinking, creative thinking, critical thinking, and professional ethics. Interpersonal learning outcomes focus on individual and group interactions, such as, teamwork, leadership, and communication. Product, process, and system building skills focus on conceiving, designing, implementing, and operating systems in enterprise, business, and societal contexts.

**A CDIO EDUCATION SHOULD BE BASED ON CLEARLY ARTICULATED PROGRAM GOALS AND STUDENT LEARNING OUTCOMES, SET THROUGH STAKEHOLDER INVOLVEMENT.**

**THE DESIGN AND EXECUTION  
OF THE EDUCATION  
SHOULD BE BASED ON  
IDENTIFIED BEST PRACTICE  
AND APPLICATION OF  
SCHOLARSHIP ON LEARNING.**

Learning outcomes are reviewed and validated by key stakeholders—groups that share an interest in the graduates of engineering programs—for consistency with program goals and relevance to engineering practice. In addition, stakeholders help to determine the expected proficiency level, or standard of achievement, for each learning outcome.

Setting specific learning outcomes helps to ensure that students acquire the appropriate foundation for their future. They allow effective design of the education, implementation of teaching and learning, and aligned assessment.

The third and final idea is that the design and execution of the education should be based on identified best practice and application of scholarship on learning. The salient features of the vision are:

- learning outcomes met by constructing a sequence of integrated learning experiences, some of which are experiential, that is, they expose students to the experiences that engineers will encounter in their profession.
- a curriculum organized around mutually supporting disciplinary courses with CDIO activities highly interwoven, forming the curricular structure for the sequence of learning experiences
- design-implement and hands-on learning experiences set in both the classroom and in modern learning workspaces as the basis for engineering-based experiential learning
- active and experiential learning, beyond design-implement experiences, that can be incorporated into disciplinary courses
- a comprehensive assessment and evaluation process

We must find ways to realize this vision by strengthening the collective skills of the faculty by re-tasking existing resources, while largely using existing resources. Together with the first two key ideas, on context and learning outcomes, these approaches are incorporated into the CDIO Standards of best practice.

### CDIO DUAL IMPACT LEARNING

The essential feature of CDIO is that it creates dual-impact learning experiences that promote deep learning of technical fundamentals and of practical skill sets. CDIO uses modern pedagogical approaches, innovative teaching methods, and new learning environments to provide concrete learning experiences. These experiences create a cognitive framework for learning the abstractions associated with the technical fundamentals, and provide opportunities for active application that facilitates understanding and retention. Thus, these concrete learning experiences are of dual impact. More obviously, they impart learning in personal and interpersonal skills and product, process, and system building skills. More subtly, at the same time they provide the pathway to deeper working knowledge of the fundamentals.

The objective of educational design is, therefore, to craft a series of concrete learning experiences, including design-implement exercises, which will both teach the skills, and at the same time

Mechanical engineering students at Denmark Technical University construct a model of a portable shelter they designed in a CDIO design-build course. The CDIO Initiative, which started in MIT Aero-Astro and DTU joined in 2002, has been adopted at 24 schools throughout the world. (DTU photograph)



promote the deeper understanding of the fundamentals, and thus allow the CDIO goals to simultaneously be met.

**THE GOAL OF THE  
CAPSTONE COURSE IS TO  
IMMERSE UNDERGRADUATES IN  
ALL ASPECTS OF THE LIFECYCLE  
DEVELOPMENT OF AN ENGINEERING  
PRODUCT AND THEREBY EXPOSE  
STUDENTS TO IMPORTANT ASPECTS  
OF SYSTEMS ENGINEERING  
THAT ARE NOT EXPERIENCED IN  
CONVENTIONAL LABORATORY AND  
DESIGN COURSES.**

One example is Aero-Astro's three-semester capstone course. The goal of the capstone course is to immerse undergraduates in all aspects of the life cycle development of an engineering product and thereby expose students to important aspects of systems engineering that are not experienced in conventional laboratory and design courses. This past year, the three-semester sequence, which started with students in the second term of their third year, allowed students to develop a legged interplanetary rover. Under the guidance of Professor David Miller, they experienced the formal reviews, carrier integration, customer communication, systems integration, procurement practices, industry collaboration, hardware qualification and many other stages in the evolution of an aerospace product. By experiencing the full life cycle, the students gain a better appreciation for how decisions made early in the design impact downstream activities.

By conducting the development over three semesters, the students gain four very important experiences. First, they are provided with the time to make and learn from mistakes. If students are continuously guided towards the correct decision, they never have the opportunity to learn to recognize bad decisions or, more importantly, learn how to recover from bad decisions. Second, the length of the project allows the students to work through interpersonal conflicts and, as a result, develop into a cohesive team that not only works well together, but also has the confidence to assume responsibility and guide the development of the product. Third, the students are exposed to various forms and iterations of technical communications. Conducting reviews and writing multiple revisions of design documents for the same project allows the students to build upon their work, thereby not



only strengthening the design, but also their communications skills. Fourth, the duration allows the students to take the design to a higher level of quality than a conventional one or two semester sequence would allow. Since quality is an essential element of any aerospace product, this experience is valuable to their future careers.

Scheduled for publication this summer by Springer Publishing is *Rethinking Engineering Education, The CDIO Approach*, a book detailing the CDIO process. The worldwide expansion of CDIO will continue, with more universities from China, Europe, and the Middle East about to join. The most important progress is taking place in the classroom and teaching workspaces, where every day students and faculty are working to achieve the desired learning.

Edward Crawley is the Ford Professor of Engineering in the MIT Aeronautics and Astronautics Department and is former head of the Department. He is a founder and principal leader of the CDIO Initiative. Professor Crawley acknowledges the contributions made to this article by colleagues within the Department, and at participating universities worldwide. Additionally, underlying contributions of educational scholars, and those in industry, working tirelessly to communicate their needs, are equally important. He may be reached at [crawley@mit.edu](mailto:crawley@mit.edu)



Its four rotors frozen by the camera, a quadrotor hovers above Aero-Astro Professor Jon How's hand. Flying autonomously, the UAV will stay within a 20 cm box-shaped space — a feat exceeding the capabilities of the best human pilots. (William Litant photograph)

# RAVEN: TESTBED FOR AUTONOMOUS UAVs

By Jonathan How

Unmanned aerial vehicles have become vital warfare and homeland security platforms. They significantly reduce costs and the risk to human life, while amplifying warfighter and first-responder capabilities. These vehicles have been used in the Iraq war and during Hurricane Katrina rescue efforts with some success, but there remain technological barriers to achieving the vision of multiple UAVs operating cooperatively with other manned and unmanned vehicles in the national airspace and beyond.

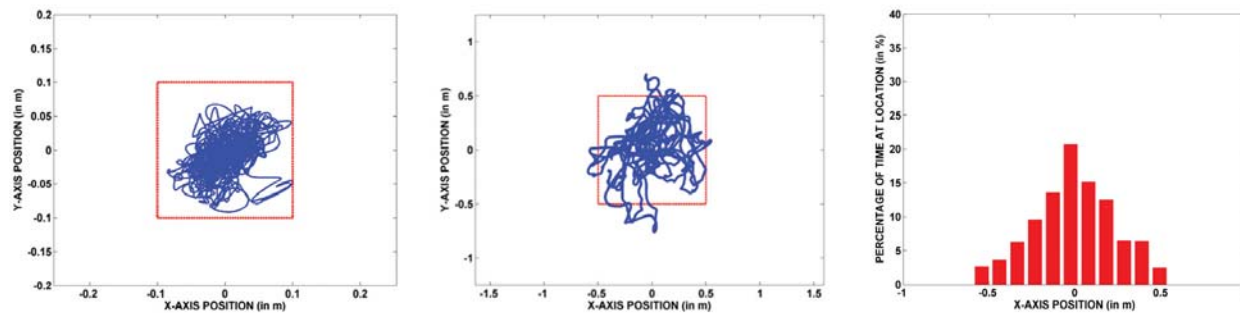
maps the region for the human response team, searches for victims, interviews witnesses, and monitors the overall environment for threats. The UAVs must coordinate to ensure that the many tasks of this mission are performed as efficiently and effectively as possible, given the uncertainty in the terrain and poor knowledge of the scope of the mission. In another scenario, a team of UAVs could be used to protect a military convoy — fanning out to provide full surrounding surveillance while providing the ability to split off to take a more detailed look at targets of interest. Then, as fuel is used up, or unexpected mechanical problems occur, the UAVs would self-diagnose the problem, summon a replacement vehicle, and land on a mobile support platform to be replenished or sent to repair. In such a mission, the UAVs would coordinate to ensure that they

Key among the challenges to future unmanned aerial vehicle use is the need to extend and distribute the team planning and control to achieve coordinated UAV behaviors in the presence of significant uncertainty about the operating environment. For example, consider a scenario in which a team of UAVs responds to a disaster site,

**UAVS WOULD SELF-DIAGNOSE A PROBLEM, SUMMON A REPLACEMENT VEHICLE, AND LAND ON A MOBILE SUPPORT PLATFORM TO BE REPLENISHED OR SENT TO REPAIR.**

are located in the best vantage points, given the terrain, to maintain full coverage around the convoy, and to ensure that routine, or unexpected, mechanical failures do not result in significant degradation in the team performance.

Researchers have recently developed algorithms to achieve cooperative UAV behaviors. A key step towards transitioning these high-level algorithms to future missions is to successfully demonstrate that they can be implemented in testbeds that use similar-sized (or scaled-down) vehicles operating in realistic environments. Doing experiments on scaled testbeds highlights the fundamental challenges associated with performing multi-day autonomous system operations with numerous human operators managing both high-level mission goals and autonomous UAVs conducting individual tasks. These challenges include



### Autonomous hover tests

Typical results from a 10-minute quadrotor hover test are shown in the figure on the left. In this test, a single quadrotor is commanded to hold its position at  $(x,y,z) = (0,0,0.7)$  m for 10 minutes. There are three plots depicted, including a plot of the vehicle's x- and y-positions during this test. The dashed red box in the image is  $\pm 10$  cm from the center point. As shown, the vehicle maintains its position inside this 20 cm box during the entire flight.

Numerous hover tests were performed with a foam airplane, which is a very challenging flight configuration. Typical results are shown

in the center figure, in which the vehicle is commanded to hold its position at  $(x_E,y_E,z_E) = (0,0,0.7)$  m for five minutes while it maintains its position and attitude. The dashed red box in the picture is  $\pm 0.5$  m from the center point. The vehicle maintains its position inside this 1 m box for most of the five minute test period. In the figure on the right, the histogram of the vehicle's x position confirms that it is within a 20 cm box around the target point more than 63% of the time.

planning for a large team in real-time with computation and communication limits; developing controllers that are robust to uncertainty in situational awareness, but are sufficiently flexible to respond to important changes; and using communication networks and distributed processing to develop integrated and cooperative plans.

Researchers have also developed a variety of research platforms to study advanced theories and approaches in the development of innovative UAV concepts. However, these testbeds typically have several limitations. For example, current outdoor platforms can be tested only during good weather and environmental conditions. Since most outdoor UAV test platforms can be flown safely only during daylight operations, these systems cannot be used to examine research questions related to long-duration missions, which may need to run overnight. In addition, many of these vehicles are modified to carry additional vehicle hardware for flight operations. Redesigned to meet payload, onboard sensing, power plant, and other requirements, they must be flown in specific environmental conditions, unrelated to flight hour constraints, to avoid damage to the vehicle hardware. These external UAVs also typically require a large support team, which makes long-term testing difficult and expensive.

### THE AEROSPACE CONTROLS LABORATORY

The MIT Aeronautics and Astronautics Department's Aerospace Controls Laboratory set out to research and overcome these challenges. ACL investigates estimation and control systems for aerospace systems, with particular attention to distributed, multivehicle architectures. Example applications involve cooperating teams of UAVs or formation-flying spacecraft. The research goal is to increase the level of autonomy in these systems by incorporating higher-level decisions, such as vehicle-waypoint assignment and collision avoidance routing, into feedback control systems. Core competencies include optimal



Graduate student Per Adrian Alexander Frank observes a foam aircraft as it autonomously hovers nose-up in the Aerospace Controls Lab — an extremely challenging, and successful, test. (William Litant photograph)

estimation and control, optimization for path-planning and operations research, receding-horizon/model predictive control, and Global Positioning Systems. This research has been demonstrated on several testbeds, including a team of eight rovers operated indoors and seven UAVs flown outside.

**A KEY RAVEN FEATURE IS A GLOBAL METROLOGY SYSTEM THAT YIELDS ACCURATE, HIGH BANDWIDTH POSITION AND ATTITUDE DATA FOR ALL VEHICLES IN THE ROOM.**

ACL experiments highlighted both the benefits and limitations of the testbeds. Based on these experiences, we developed the Real-time indoor Autonomous Vehicle test Environment, or RAVEN. RAVEN's purpose is to examine long-duration missions in a controlled environment. The facility is designed to test and examine a wide variety of multivehicle missions using both autonomous ground and air vehicles. A key RAVEN feature is a global metrology system that yields accurate, high bandwidth position and attitude data for all vehicles in the room. Since the position markers are lightweight, the position system can sense position and attitude without adding significant payload to the vehicles. Thus, the platform can use small, essentially unmodified, radio-controlled vehicle hardware such as electric helicopters and airplanes. This frees researchers from overly conservative flight testing, and allows us to simultaneously fly eight or more vehicles in the confines of the lab.

An additional benefit is that one operator can set up the platform in fewer than 20 minutes, for flight testing multiple UAVs so researchers can perform a large number of test flights in a short period of time with little logistical overhead. Furthermore, since the system autonomously manages the navigation, control, and tasking of realistic air vehicles during multivehicle operations, researchers can focus on the algorithms associated with the team coordination rather than the details of the implementation. These properties greatly enhance the utility of the testbed, making it an effective rapid prototyping environment for multivehicle mission management algorithms.

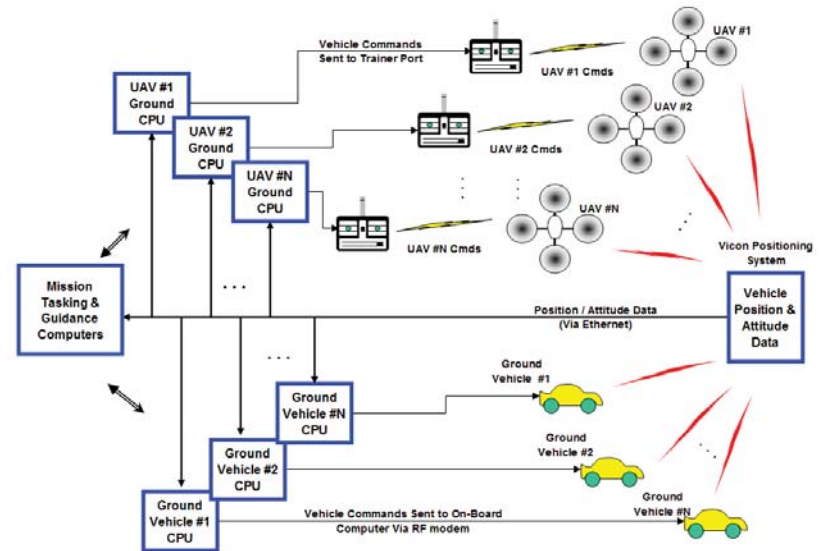
## ARCHITECTURE

In our lab, the control algorithm and command data for each vehicle is processed by a dedicated computer and sent over a USB connection from the vehicle's control computer to the trainer port interface on the vehicle's transmitter. All computing for this system is performed on ground-based computers. A Vicon MX camera system measures the position and attitude for each vehicle in the testbed at rates up to 120 Hz. This motion capture system provides a simple, baseline capability for sensing and controlling the vehicle motion, which enables researchers to explore research topics, such as multivehicle coordination, vision-based navigation and control, or new propulsion mechanisms such as flapping flight.

Just as GPS spurred the development of large-scale UAVs, we expect this new sensing capability to have a significant impact on 3D indoor flight, which has historically been restricted to very small areas.

## RESULTS

RAVEN comprises a variety of rotary-wing, fixed-wing, and ground-based R/C vehicles. However, most testbed flight experiments are performed using the Draganflyer V Ti Pro quadrotor. While easier to fly than a standard helicopter, quadrotors are unstable and there is a strong coupling between the attitude control and the position loops. The four motors' speeds must be rapidly and precisely adjusted to balance the vehicle and overcome any external disturbances. Thus, quadrotors are



This diagram depicts the components and setup of RAVEN's integrated control system. Since the platform's primary computing, data collection, and sensing resources are offboard the vehicles, users can examine research questions related to autonomous multivehicle operations using simple, inexpensive vehicles.

**IN OUR TYPICAL 10-MINUTE TESTS, WE HAVE ACHIEVED THE ABILITY FOR THE DRAGANFLYER TO HOVER AUTONOMOUSLY IN A DIMENSION HALF THE SIZE OF THE VEHICLE ITSELF.**

difficult to fly manually without significant operator training. In our typical 10-minute tests, we have achieved the ability for the Draganflyer to hover autonomously in a dimension half the size of the vehicle itself. The quadrotor stays inside a 20 cm box during the entire flight, far exceeding the capabilities of our best human pilot.

Tests have also been performed with a foam airplane. We first tackled a nose-up hover condition. This is a challenging flight configuration for an aircraft because there is limited airflow over the rudder and elevator that must be used to control the vehicle position and these surfaces are partially blocked by the wing ailerons which are used to offset the motor torques, which are varied to control the aircraft altitude.

Again, tests confirm that the vehicle can be made to autonomously hover within a 20 cm box more than 63% of the time. As with the quadrotor, these results far exceed the capabilities of our best pilots, and were developed in fewer than two months.

**WHILE THESE ARE IMPRESSIVE RESULTS ARE FOR A SINGLE VEHICLE, A MORE IMPORTANT FEATURE OF RAVEN IS THAT WE CAN ROUTINELY OPERATE FIVE VEHICLES AT THE SAME TIME, AND HAVE FLOWN AS MANY AS 10.**

While these are impressive results are for a single vehicle, a more important feature of RAVEN is that we can routinely operate five vehicles at the same time, and have flown as many as 10.

RAVEN also provides a superb learning experience for students, who have been instrumental in its development. Currently, RAVEN forms the basis for seven Aero-Astro and Electrical Engineering and Computer Science graduate students' thesis research. Five Aero-Astro and Electrical Engineering and Computer Science undergraduate students, working under MIT's Undergraduate Research Opportunities Program, complete the team.

Our main goal as we move forward is to demonstrate the use of health management tools to improve the performance of a team of UAVs performing persistent surveillance tasks. We plan to demonstrate this, in collaboration with Boeing Phantom Works, during the summer of 2007. RAVEN is also being used to perform flight demonstrations of coopera-



tive planning and control concepts under development for the Air Force Office of Scientific Research. We are using funding from the MIT Aeronautics and Astronautics Department and the School of Engineering for several additional research projects, including human interaction with autonomous robots; coordination, control, and sensor fusion over intermittent communication networks; control of micro and nano air vehicles, including flapping flight; autonomous acrobatic aircraft; and flight control using other sensors suites, such as vision, using reduced Vicon information. RAVEN is an impressive facility for multivehicle testing — we have only just started to explore its full capabilities.

Jonathan P. How is an Associate Professor in the MIT Aeronautics and Astronautics Department. His research interests include using operations research tools, such as mixed-integer programming, to optimize the coordination and control of autonomous vehicles in dynamic uncertain environments. He was the recipient of the 2002 Institute of Navigation Burka Award, is the Raymond L. Bisplinghoff Fellow for Aero-Astro, is an AIAA Associate Fellow, and an IEEE senior member. He may be reached at [jhow@mit.edu](mailto:jhow@mit.edu)

Robyn Allen at the MIT Museum with a car her Vehicle Design Summit built to enter the Automotive X-Prize 200 mpg vehicle competition. (William Litant photograph)



## Three Aero-Astro students blend engineering skills and social conscience to better the world **HAND AND MIND...AND HEART**

MIT Aeronautics and Astronautics students are members of a unique group. The scope of their skills and interests is astounding. When their innate talents are fortified by their experiences and learning at MIT, they become not just engineers, but engineering leaders. However, some of them become leaders even before they have donned caps and gowns. There is little more exciting and rewarding than to see our students employing their engineering know-how to tackle some of the world's most pressing social issues. Here, we learn from three of our students how they are working to better the lives of others: one by fostering community and academic relationships with a developing country; another, through her own non-profit corporation, improving the lives of impoverished street children; and a third who has founded a consortium to study sustainable transportation technologies. The MIT motto, "Mens et Manus," implores our community to employ its "Minds and Hands." These students add a third element: they are using their minds, their hands—and their hearts. Here, in their own words, are their stories.

### **ROBYN ALLEN**

I'm Robyn Allen, I'm an Aero-Astro senior, and my goal is to contribute to ending global warming. I am the founder and co-director of the Vehicle Design Summit, an international, student-led consortium aimed at leapfrogging sustainable transportation technologies.

The Department's multidisciplinary design challenges and overall systems pedagogy drew me to study aero-astro, but in addition to my technical learning objectives, I had an insatiable curiosity for learning something else: how does one build and sustain a highly innovative design team such as the one that built the SR-71 Blackbird? I believe that a number of such teams all working on different aspects of global energy efficiency are a prerequisite to resolving the catastrophic climate change issues that face us today.

The Vehicle Design Summit aspires to be one such design team. We seek teams of university

students from up to 50 schools around the world (so far we have 25 such teams in 15 countries) to each design and build subsystems of a single 200 mpg-equivalent automobile for entry into the Automotive X-Prize competition <http://www.xprize.org>.

I steer both the technical vehicle objectives and overall structure of the consortium. Last summer during our pilot project, we invited and hosted 55 students from 21 different universities in 11 countries for a nine-week, all-out, 24/7 design-build program. All of these students worked as volunteers all summer, creating four full-scale driving prototypes from scratch. Our core managers recruited the participants, raised the money, sourced and ordered all of the hardware components, ran design reviews and evaluated team performance, developed and implemented the schedule of technical milestones, and handled requirements evolution.

Experiences such as the 16.82 Mars rover course, and mentorship from Aero-Astro alum John Langford, president of Aurora Flight Systems, enabled me to advance both my academic and pre-professional goals through VDS. More importantly, Aero-Astro's commitment to student-led initiatives enables VDS to make this opportunity available to many MIT students wishing to participate. Without this advice and guidance, it would never have been possible for me to be in the lead of a growing 500-person global team as a 21-year-old.

Ending global warming is one thing, but to put electrical, mechanical, and aerospace engineers next to management students, materials scientists, programmers, future policymakers, journalists, economists, physicists, and dreamers in a capstone class which creates both a marketable product and a story that captures the world's imagination — now that is a revolution I want to make happen.

### DANIELLE ADAMS

I'm Danielle Adams and I completed my bachelor's degree in Aero-Astro in 2005. I'm a second year Masters candidate in both Aero-Astro and the Technology and Policy Program. For my Master's research, I'm exploring the conditions under which technology that relies on satellites can be used to meet needs in developing countries. I'm particularly interested in how such technology might be applied in Africa. However, my interest in Africa extends far beyond my research; it comes from years of volunteerism in both the eastern and southern areas of the continent.

I first visited Africa in 2001 when I volunteered with an agency that serves homeless children in Kenya. That summer I taught reading and math lessons to young girls from the Nairobi slums. I was able to return to Kenya in 2002 and 2004 and do tutoring in math and science with some of the same children. In 2005, with the urging of department head Professor Wesley Harris, I started working on behalf of Aero-Astro to foster a relationship between our department and the University of Pretoria. In particular, our department collaborates with the UP Department of Mechanical and Aerospace Engineering. We are developing plans to establish a student exchange, student community service internships, and faculty research collaborations with this university.

In June 2006 I traveled with a team of six others from MIT to the Cape Peninsula University of Technology in Cape Town, South Africa. There, we conducted a week-long communications seminar for a class of fourth year mechanical engineering students. The focus of the training was to give them confidence in technical presentations.



On a visit to South Africa, Aero-Astro master's candidate Danielle Adams discusses joint projects for MIT students and their University of Pretoria colleagues with UP School of Engineering Chairman Josua Meyer (right). Joining Adams are (from left) Aero-Astro Head Professor Wesley Harris, UP Mechanical Engineering Professor Stephan Heyns, and MIT Lecturer Peter Young. (William Litant photograph)

My long-term goal is to serve as a consultant to developing country governments on the topic of space based technology. I am eager to encourage young minority and women students to learn math and science skills, and I hope that my work will enable many new leaders to be educated.

While at first it appeared that volunteer work could have little relation to what I was learning about aerospace engineering at MIT, I quickly found ways to connect my interest in Africa with my interest in space. I added science to the lessons I was teaching former street girls in Kenya and helped them learn about the properties of airplanes. And then, the Department gave me an opportunity to work on developing a relationship with an African university in Pretoria, South Africa. And, now I've fully integrated my passions: I am researching how satellite-based technology can be used to meet national needs in African countries.

### **NICKI LEHRER**

My name is Nicki Lehrer. I'm an Aero-Astro senior and the founder and president of the nonprofit organization Children of Guayaquil, the purpose of which is to help Ecuador's most impoverished street children. My adventure began in the fall of 2005 when I took a semester leave of absence to live and work in the poorest regions of Ecuador. The journey landed me in the southern town of Pascuales where I was struck by the number of children surviving on the streets during the day — without food, without clothing, without shoes, and without education.

Returning to the States, I founded Children of Guayaquil, which is named for the most populous city in Ecuador. The organization is dedicated to providing a safe haven for these children, protecting them from the drugs, alcohol, and prostitution that plague the streets of the town. Since the foundation's incorporation in 2006, I have managed to raise more than half of the money needed for construction of a children's community center in Pascuales; collected thousands of pounds of clothing, shoes, toys, and school supplies for the children;

and united leaders from the region to work together towards the common goal of providing a better future for the children.

As an additional benefit of this project, I have fostered a relationship between MIT and the Ecuadorian University of San Francisco. The goal is to encourage international cooperation between students and professors who are collaborating and learning from each other while working to help the children of Pascuales. MIT Architecture Professor Jan Wampler conducted a class last semester dedicated to the design of the community center in Pascuales. Professor Wampler's entire class joined me in Ecuador during the 2007 MIT Independent Activities Period to present its models and drawings at the town celebration. More than 800 people from Pascuales came to the celebration to learn and participate. There was music, food, dancing, and laying of the first stone where the children put their hand prints in the concrete to mark the start of a better future.

In the future, I look forward to taking a more technical approach, addressing such needs as clean water, better electricity, and drainage system. The thought processes and problem solving skills that I have learned through my Aero-Astro curriculum really helped me approach the challenges that arise in this type of work. Although the application is very different from what we are used to in a class setting, my engineering education from MIT continues to be very useful in helping to make this project a success.

For more information, to learn about the children that are receiving support, see pictures, and find out how you to help, please visit <http://www.ecuadororphans.org>.



Nicki Lehrer with Andrea, a 10-year-old who will soon be a beneficiary of a community center that Leherer is organizing for impoverished children in Pascuales, Ecuador.

Bob Liebeck (right) at NASA's Dryden Research Center for tests of the blended-wing X-48B aircraft. With Liebeck are Boeing Chief Engineer Norm Princen (left) and Cranfield Aerospace Chief Engineer Dave Dyer. (Photo courtesy Bob Liebeck)



## Faculty profile HEAD OF BOEING'S BLENDED WING PROJECT BLENDS PASSIONS FOR PLANES AND TEACHING

By Bob Sales

Robert H. Liebeck, professor of the practice of aeronautics at MIT and a senior fellow at the Boeing Company, has two passions: teaching and airplanes. He likes motorcycles, too, but more on that later.

Liebeck started teaching as a graduate student at the University of Illinois Urbana-Champaign in the 1960s. He has been an adjunct professor at the University of California-Irvine since 2000 and was an adjunct professor at the University of Southern California from 1977 to 2000.

He treasures his moments in the classroom. "It is the one job where I feel I have done some good — even after

a bad lecture," said Liebeck. "I have decided that I am finally beginning to understand aeronautical engineering and I want to share that understanding with our youth."

Liebeck believes the American Institute of Aeronautics and Astronautics annual Design-Build-Fly competition provides an important practical element in the education of future aeronautical engineers. He is the faculty advisor for participants at UCal-Irvine and has encouraged MIT students to compete. He helped introduce the program at the University of Southern California. "I was proud of the performance of all three schools (in 2006)," said Liebeck, who left USC for UCal-Irvine for logistical reasons. "USC is 50



miles from where I live in Irvine,” he said, “and I can see my office at UCI from the hill I live on.”

The germ of Liebeck’s affiliation with MIT was planted 10 years ago by several Aero-Astro faculty including Professors Ed Crawley, Earl Murman, and Eugene Covert who wanted to recruit Liebeck as a Professor of the Practice. Murman notes that Liebeck’s credentials were a perfect fit with the requirements for an MIT Professor of Practice and the match was inevitable. These credentials include managing an airplane program in private industry during his 45 years at the Boeing Company; earning a Ph.D. ( University of Illinois-Urbana Champaign 1968) and publishing extensively; membership in the National Academy of Engineering (since 1992).

Liebeck was appointed to the MIT faculty in 2000. As a Professor of Practice, he makes four or five trips a year to Cambridge. “There exist few schools that compare to MIT,” he said. “Both MIT and UCI have good students. However, MIT has some unique and special students.”

Murman noted, “Bob brings incredible aircraft design experience and wisdom to the classroom, and is always eager to work one-on-one with our students. He is a wonderful mentor to young people and young faculty. We are really fortunate to have Bob as part of our faculty.”

Liebeck never completed his job application for a position at Douglas Aircraft Company in 1961 when

he was a senior at the University of Illinois. “Don’t do that,” said Professor Allen Ormsbee, who later became Liebeck’s thesis advisor. “I want you to go to graduate school. I will get you a summer job at Douglas where I am a consultant.”

Ormsbee delivered, and Liebeck skipped the graduation ceremonies to drive 2,025 miles in his 1960 Austin Healy 3000 sports car from Urbana to the Douglas Aircraft Company in Santa Monica, Calif., to begin his career. He continued his studies at Illinois for the next seven years, leaving for a summer job at Douglas as soon as classes ended in the spring, skipping commencement in 1962 and 1968, when he received a master’s and a Ph.D., respectively. He joined the company full time in 1968 and remained on the payroll as Douglas became McDonnell Douglas and then Boeing. It’s been 46 years and counting. “I have never interviewed for a job or filled out a job application,” said Liebeck, who celebrated his 69th birthday in February.

For the record, Liebeck wore University of Illinois colors at three UCal-Irvine honors graduation ceremonies where honors students are accompanied by professors they believe played a key role in their success. “This experience I believe was more rewarding than my own graduation,” he said.

Liebeck’s thesis was titled “Optimization of Airfoils for Maximum Lift,” a topic suggested by Ormsbee and the



An avid motorcyclist, Bob Liebeck, shown here near Yosemite National Park, enjoys touring aboard his Honda VFR Nighthawk. (Photo courtesy Bob Liebeck)

late A.M.O. Smith of Douglas, who encouraged him to continue the research. The revolutionary devices are now called “Liebeck airfoils” in the industry. Originally designed in the ’70s for high altitude airplanes, a Liebeck airfoil will be used in the NASCAR Car of Tomorrow scheduled to be unveiled this year.

In his spare time, Liebeck has designed wings for Indianapolis 500 and Formula One racing cars, the keel for the yacht that won the America’s Cup in 1991 and the wing for a World Championship acrobatic airplane, an unmatched triple crown. “This could be summarized as victory on land, sea, and air,” he said.

Liebeck is a member of the National Academy of Engineering and a world-renowned authority in the fields of aerodynamics, hydrodynamics, and aircraft design. He attained world recognition starting in the 1970s with his novel designs for high-lift “Liebeck airfoils.” He has made substantial contributions to a variety of related fields, including propeller design, windmill analysis,

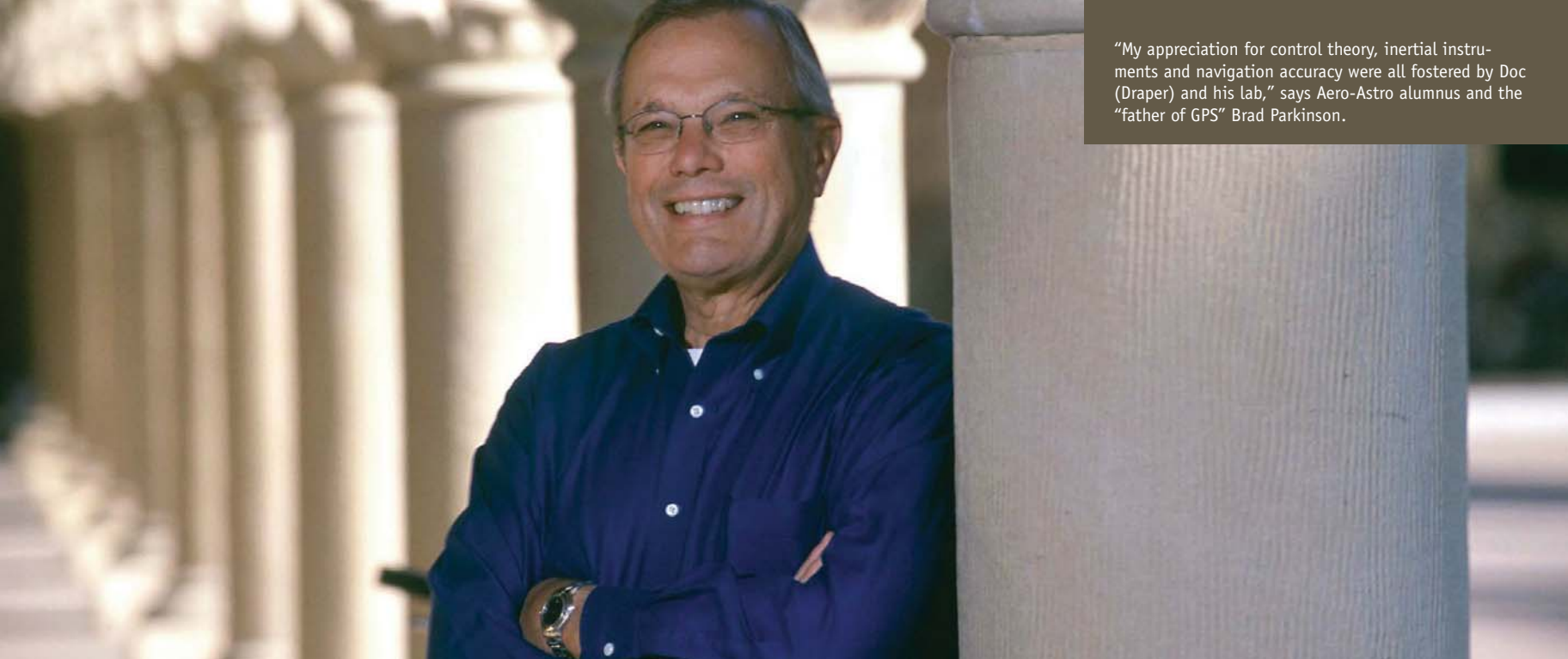
wing design for supersonic transports, and the design of high-altitude unmanned aircraft.

For the past 15 years, Liebeck has been program manager of Boeing’s Blended Wing Body project, developing a 500-passenger “flying wing” aircraft. “The BWB project continues to both progress and remains a challenge,” Liebeck said. The BWB X-48B, a subscale prototype with a 21-foot wingspan and three 50-pound turbojet engines, is undergoing tests.

At the 50th reunion of Wheaton High School’s class of 1956 last September, Liebeck and his classmates were asked to list their interests and hobbies. Golf, travel, grandchildren were the most popular answers among his peers, most of whom are retired. Liebeck’s were motorcycles, running, and writing a book on airplane design. He runs two to three miles every other day and competes in the occasional 10K race.

His fascination with motorcycles began as a teenager in Wheaton, IL. Liebeck acquired his first motorcycle at age 14, a Whizzer — basically, a motorized bicycle — with an ear-splitting exhaust. At the University of Illinois he said he had guilt pangs when he upgraded to a BSA 500 single with a louder exhaust. He now owns four cycles, two of which are quiet. “I no longer feel guilty,” he said.

Bob Sales, a former executive editor of the Boston Herald and editor of the Boston Phoenix, teaches journalism at Boston University and Northeastern University. He may be reached at [bobsales@att.net](mailto:bobsales@att.net).



"My appreciation for control theory, inertial instruments and navigation accuracy were all fostered by Doc (Draper) and his lab," says Aero-Astro alumnus and the "father of GPS" Brad Parkinson.

## Alumnus profile **BRAD PARKINSON'S DIRECTION LED HIM—THEN HE LED THE REST OF THE WORLD—TO GPS**

By Bob Sales

His father assumed Bradford W. Parkinson would follow in his footsteps to MIT when he graduated from the prestigious all-boys Breck School in St. Paul, Minn., in 1952. But Brad had his heart set on the U.S. Naval Academy, alma mater of both his Uncle Webster Smith and Rich Fontaine, a highly admired Eagle Scout from his hometown of Minneapolis, who rose to the rank of admiral during his Navy career.

"If that's what you want to do, it's okay," Herbert Parkinson (SB 1927, Architecture) told his only son. The decision merely postponed his MIT experience.

Upon graduation from the Naval Academy in 1957, Brad Parkinson could not be a pilot, because he was nearsighted, but accepted a commission in the Air Force. The primary reason for choosing that service was the postgraduate education they offered. He served

as the chief Communications-Electronics officer at an early warning station before the Air Force sent him to MIT for graduate school two years later.

At MIT, Parkinson, who went on to become the father of the Global Positioning System, developed the knowledge and skills that allowed him to guide that breakthrough research project. His thesis work at the Instrumentation Laboratory, known today as the Dr. Charles Stark Draper Laboratory, laid the groundwork.

“My appreciation for control theory, inertial instruments, and navigation accuracy were all fostered by Doc and his lab,” Parkinson said. “Without that background, it is very unlikely that I would have been involved in GPS, gunships, or eventually a tenured professor at Stanford. While the Naval Academy was a good solid engineering school, I had to shift gears when I got to MIT.” For instance, he felt overwhelmed by the rigorous standards required for Atomic and Nuclear Physics (8.051). “My undergraduate physics at USNA did not prepare me for this course, so I had to really work on it,” he said. “In the end, I received an A, but that was only after an enormous effort.”

MIT wasn't all study and grind. Intramural hockey provided the fun and games. A group of mostly Air Force officers formed an Aero-Astro department team that won its league title. A team from Graduate House dominated by Canadians won the other league. The teams met in a two out of three championship series in 1961.

“All players on both sides were overachieving graduate students who hated to lose,” recalled Parkinson, who played left wing on the Aero-Astro team. “We were outclassed and sad to say, during the second period a general fight broke out. The MIT athletic director was in the stands and utterly shocked — maybe he never played hockey.” Play was halted and Graduate House was declared the winner. The series resumed two nights later. “By then, we all had regained our composure,” Parkinson said. “The Graduate House Canadians won easily and we all repaired to a local tavern and had a few beers as good friends.”

Parkinson received his M.S. in 1961 and spent three years as a missile guidance analyst before embarking upon a Ph.D. at Stanford, which he was awarded in 1966. Promoted to major, he was assigned to the Aerospace Research Pilots School and flew training missions with the test pilots. After receiving an early promotion to Lieutenant Colonel, he was assigned in 1969 to develop the A/C 130 Gunship, on which he later flew 26 combat missions during the Vietnam War, earning a Bronze Star, two Air Medals and a Presidential Unit Citation. A framed photo of the gunship hangs in his office.

Promoted to full colonel in 1972, he was assigned to lead the Air Force's new 621B program, created to design an Air Force navigation system to replace the Navy's Transit. At the time, two different groups in the Navy were also working on their own programs,

with each office strenuously advocating its design. A cooperative program obviously would be more efficient, and Parkinson was assigned to head the Joint Services Program Office in 1973. The assignment had the potential to be a career-breaker because of the intense inter-service rivalries. Parkinson made it work.

The critical design meeting took place at the Pentagon during Labor Day weekend in 1973. “I excluded all but my program office,” Parkinson said. “At the same time I wanted to architect a system which would consider all proposals. Some have asked, ‘Who invented GPS?’ The accurate answer is that no one person did. I selected concepts and technologies from all sources, but GPS most closely resembles the concept developed by the USAF program 621B.”

The joint program included Navy, Army, Air Force, and Marine Corps officers. But the staff was dominated by Air Force officers with advanced degrees from prestigious schools, including MIT and Michigan. They received critical support from the civilian Aerospace Corporation. “The head of Aerospace (Dr. Ivan Getting) had been a strong advocate for a system, although he had no role in the actual development,” Parkinson said.

Brad Parkinson (center) with Frank Butterfield of The Aerospace Corporation and Navy Commander Bill Huston discuss GPS in the early 1970s.



“He deserves much credit for helping us get through the political snares and traps of the Pentagon.”

The GPS system unveiled for military use in 1973, which now serves scores of civilians, is virtually unchanged from Parkinson’s original design. Among the civilian uses are tracking and dispatching fleets of vehicles, including Federal Express’ trucks and planes; creating travel routes, plowing fields, even allowing parents to follow their children’s activities. None of this started until the mid-’90s. Later at Stanford, Professor Parkinson led the research that demonstrated new GPS applications including Aircraft Blind Landings, Farm Tractor Autopilots to accuracies of two inches, and use of GPS to measure spacecraft attitude.

“The problem was not the lag in civil applications but the protracted delay in completing the system,” said Parkinson. He retired from the Air Force in 1978 just as the first GPS satellites were demonstrating the new capabilities. GPS was finally declared operational in 1995. “It could have been operational at least 10 years earlier, had they just cranked out more of the phase one satellites. As soon as the DOD saw it was successful, they started loading it down with additional requirements and constraints. They also tried to cancel it on several occasions, but the civil leadership of the Pentagon usually interceded and ensured it could continue.”

As a civilian, Parkinson was a professor at Colorado State University for a year before becoming a general manager and a CEO in private industry. He joined the Stanford University faculty in 1984 as a Research Professor and became tenured a few years later. He was also the co-PI and program manager on Gravity Probe-B, a \$500M space test of the general theory of relativity. He became professor emeritus in 2000, but was recalled and still remains active in GPS research.

In 2003, he and Ivan Getting were awarded the Draper Prize “For the concept and development of the Global Positioning System (GPS).” His relationship with Doc Draper had come full circle.

Parkinson, who celebrated his 72d birthday in February, lives in San Luis Obispo, where he enjoys his six children and five grandchildren. He remains very active, serving on many national committees advising the Government on GPS. For a while, he hoped to resume flying. “I’m so busy that, after I canceled a refresher session for about the fourth time, I had to abandon that idea — reluctantly,” he said.

Bob Sales, a former executive editor of the Boston Herald and editor of the Boston Phoenix, teaches journalism at Boston University and Northeastern University. He may be reached at [bobsales@att.net](mailto:bobsales@att.net).



## A Review of Aeronautics and Astronautics Department Research Laboratories: LAB REPORT

### 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 estima-

Graduate student Dan Courtney holds a diverging-cusp Hall thruster for spacecraft plasma propulsion he designed and built in Aero-Astro's Space Propulsion Laboratory. This engine departs from traditional Hall thruster design, promising both extended life and performance. (William Litant photograph)

*Information provided by the laboratories and research centers.*

tion 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: Luis Cueto, David Darmofal, Mark Drela, Robert Haimes, Cuong Nguyen, Jaime Peraire (director), Per-Olof Persson, Thomas Richter, Karen Willcox, and David Willis.

*Visit the Aerospace Computational Design Laboratory at <http://acdl.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 Jonathan How and Steven Hall.

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

### **COMMUNICATIONS AND NETWORKING RESEARCH GROUP**

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

The group is working on a wide range of projects in the area of data communication and networks with



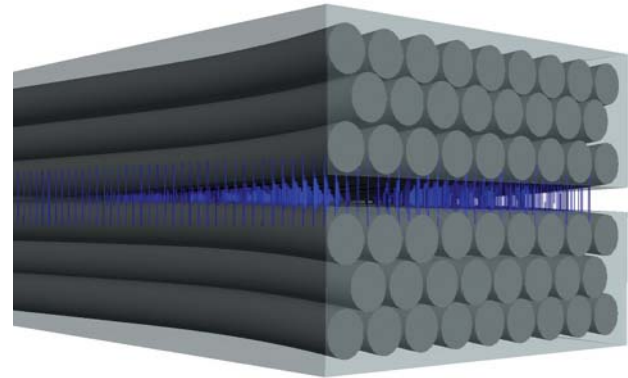
application to satellite, wireless, and optical networks. An important aspect of the group's research is the development of architectures and algorithms that are optimized across multiple layers of the protocol stack, such as the design of network protocols that are aware of the physical layer channel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

Eytan Modiano directs the Communications and Networking Research Group.

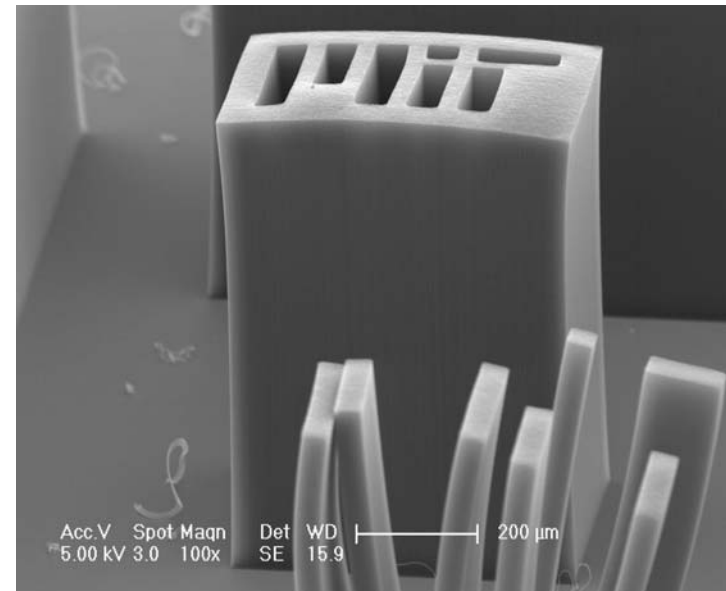
*Visit the Communications and Networking Research Group at <http://web.mit.edu/aeroastro/labs/cnrg/>*

#### **COMPLEX SYSTEMS RESEARCH LABORATORY**

Increasing complexity and coupling as well as the introduction of digital technology are introducing 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



Aligned carbon nanotube forests (bottom) and 'nanostitched' composite laminate concepts developed by Aero-Astro's Technology Laboratory for Advanced Materials and Structures as part of MIT's Nano-engineered Composite aerospace Structures (NECST) initiative. Only 1/10,000 the diameter of a human hair, these highly-ordered materials have exceptional mechanical and multifunctional properties and offer great potential for creating the next generations of advanced aerospace structures.



lab applies a systems approach to engineering that includes building technical foundations and knowledge and integrating these with the organizational, political, and cultural aspects of system construction and operation.

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

CSRL faculty include Nancy Leveson (director), 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, shirt-button sized high-power density gas turbine and rocket engines fabricated using silicon chip manufacturing technology; which involves extensive collaboration with the Department of Electrical Engineering and Computer Science these are; 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/index.html>*

### **HUMANS AND AUTOMATION LABORATORY**

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

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

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

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

## INTERNATIONAL CENTER FOR AIR TRANSPORTATION

The International Center for Air Transportation undertakes research and educational programs that discover and disseminate the knowledge and tools underlying a global air transportation industry driven by 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 manage-

ment; 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 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/aerastro/www/labs/ICAT/>*

Professor Missy Cummings and doctoral student Sylvain Bruni with the Humans and Automation Lab's new Mobile Advanced Command and Control Station. The lab will use the innovative command and control mobile facility, outfitted with extensive computer and communications equipment, as a testbed for human supervisory control research. (William Litant photograph)



## **LABORATORY FOR INFORMATION AND DECISION SYSTEMS**

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

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

*Visit LIDS at <http://lids.mit.edu/>*

## **LEAN 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), Earl 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 fosters breakthrough technological, operational, policy, and workforce advances for the betterment of mobility, economy, national security, and the environment. PARTNER represents the combined talents of 12 universities, three federal agencies, and 50 advisory board members, the latter spanning a range of interests from local government, to industry, to citizens' community groups. During 2006-07, PARTNER continued to expand its research portfolio, added participating universities and advisory board members, and forged international collaborations. Harvard University's School of Public Health and the University of North Carolina joined PARTNER.

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 poli-

cies, technologies and operational options for enabling environmentally responsible and economically viable air transportation growth.

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

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

Current PARTNER MIT personnel include Ian Waitz (director), Karen Willcox, James Hileman, Christine Taylor, Karen Marais, Malcom Weiss, Stephen Connors, William Litant, Jennifer Leith, and 10-15 graduate students.

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

### **SPACE PROPULSION LABORATORY**

The Space Propulsion Laboratory, part of the Space Systems Lab, studies and develops systems for increasing performance and reducing costs of space propulsion. A major area of interest to the lab is electric propulsion in which electrical, rather than chemical energy propels spacecraft. The benefits are numerous 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, and Paulo Lozano and Oleg Batishchev are key participants.

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

### **SPACE SYSTEMS LABORATORY**

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

Major SSL initiatives study the development of formation flight technology. The SPHERES facility, which began operations aboard the International Space Station in May 2006, enables research of algorithms for distributed satellites systems, including telescope formation flight, docking, and stack reconfiguration. The Electromagnetic Formation Flight testbed is a proof-of-concept demonstration for a formation flight system that has no consumables; a space-qualified



version is under study. The MOST project studies multiple architectures for lightweight segmented mirror space telescopes using active structural control; its final product will be a ground-prototype demonstrator. Multiple programs research the synthesis and analysis of architectural options for future manned and robotic exploration of the Earth-Moon-Mars system, as well as real options analysis for Earth-to-Orbit launch and assembly. In addition, SSL is developing technologies for low cost star trackers and mappers, stereographic imaging systems, and space propulsion.

SSL faculty and staff include David W. Miller (director), Raymond J. Sedwick (associate director), John Keesee, Olivier de Weck, Edward F. Crawley, Daniel Hastings, Annalisa Weigel, Manuel Martinez-Sanchez, Paulo

Lozano, Oleg Batishchev, Alvar Saenz-Otero, Paul Bauer, SharonLeah Brown, Margaret Bryan, and Marilyn E. Good.

*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 facili-

tate and hasten the exploitation of advanced materials systems in, and the use of, various advanced structural applications and devices.

The laboratory has recently broadened its interests from a strong historical background in composite materials, and the name change from the former 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
- characterization of carbon nanotube bulk engineering properties
- composite tubular structural and laminate failures
- MEMS-scale mechanical energy harvesting modeling, design, and testing
- durability testing of structural health monitoring systems
- thermostructural design, manufacture, and testing of composite thin films and associated fundamental mechanical and microstructural characterization
- continued efforts on addressing the roles of lengthscale in the failure of composite structures

- numerical and analytical solid modeling to inform, and be informed by, experiments
- 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 structural specimens such as coupons, shells, shafts, stiffened panels, and pressurized cylinders, made of composites, active, and other materials. A recent addition is a facility for synthesizing carbon nanotubes. TELAMS testing capabilities include a battery of servohydraulic machines for cyclic and static testing, a unit for the catastrophic burst testing of pressure vessels, and an impact testing facility. TELAMS maintains capabilities for environmental conditioning, testing at low and high temperature, and in general and hostile environments. There are facilities for microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization.

With its ongoing, linked, and coordinated efforts, both internal and external, 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. This commitment is exemplified in the newly formed Nano-engineered Composite aerospace STructures Consortium, an industry-supported center for developing hybrid advanced composites. In all these efforts, the laboratory and its members continue their extensive collaborations with industry, government organizations, other academic institutions, and other groups and faculty within the MIT community.

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

*Visit the Technology Laboratory for Advanced Materials and Structures at <http://web.mit.edu/telams/index.html>*

#### **WRIGHT BROTHERS WIND TUNNEL**

Since its opening in September 1938, The Wright Brothers Wind Tunnel has played a major role in the development of aerospace, civil engineering and architectural systems. In recent years, faculty research interests generated long-range studies of unsteady airfoil flow fields, jet engine inlet-vortex behavior, aeroelastic tests of unducted propeller fans, and panel methods for tunnel wall interaction effects. Industrial testing has ranged over auxiliary propulsion burner units, helicopter antenna pods, and in-flight trailing cables, as well as concepts for roofing attachments,

a variety of stationary and vehicle mounted ground antenna configurations, the aeroelastic dynamics of airport control tower configurations for the Federal Aviation Authority, and the less anticipated live tests in Olympic ski gear, 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 nearly 70 years of operation, Wright Brothers Wind Tunnel work has been recorded in several hundred theses and more than 1,000 technical reports.

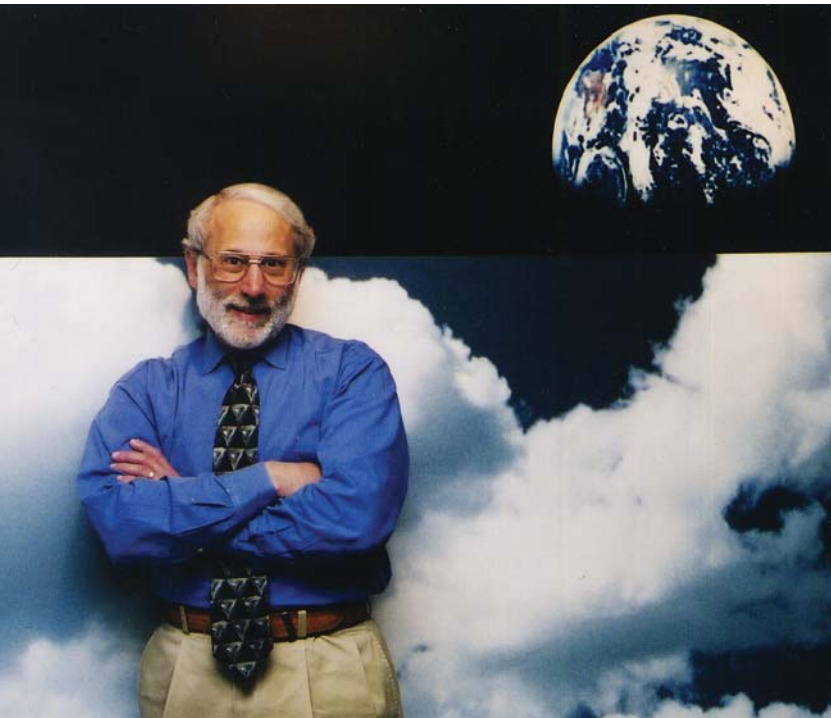
WBWT faculty and staff include Mark Drela and Richard Perdichizzi.

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

# An appreciation EARLL MURMAN MAKES EVERYTHING HE TOUCHES BETTER

By Wesley L. Harris

I met Earll Murman during the summer of 1964 at Princeton University where we were graduate students. He was party to my learning to play squash, learning



Earll Murman (William Litant photograph)

to measure wake profiles with a conical probe, and learning to navigate the trenches of graduate life.

From 1990 to 1996, as our Department head, Earll set the standard of serving the MIT Department of Aeronautics. Earll led us through the development of a strategic plan that would be Aero-Astro's road map for the next decade. He prioritized strengthening our community of scholars. He showed us how to make tough decisions without negatively impacting the essence of who and what we are. Earll made us better and stronger in so many dimensions.

During the summer of 2005, Earll returned to help the Department during a time of special need. With a full suit of armor, Earll came to our aid and served as only Earll could as our deputy department head. He led the charge to recruit new, world-class faculty members. He strengthened our relationship with MIT's Electrical Engineering and Computer Science Department. Simply put, he smoothly steered our grand ship through fields of icebergs.

Following a successful career in industry as a vice president and general manager, Earll joined the MIT faculty in July 1980 as a full professor. His MIT tenure included service as director of Project Athena (1988-1991), head of the Department of Aeronautics and Astronautics (1991-1996), director of the Lean Aerospace Initiative (1995-2002), and deputy head of the Department of Aeronautics and Astronautics (2005-2006). A member of the National Academy of Engineering, the Royal Aeronautical Society, and the Royal Swedish Academy of Engineering Sciences, Earll's peers around the globe recognize and honor him as an outstanding scholar. His seminal paper in computational fluid dynamics ushered in a new area of research. Our students, staff, and faculty have cited Earll as an outstanding academic advisor and for work to building a sense of community. Indeed, he is "a person who makes everything he touches better."

There are indeed few who have served the Department, School, Institute, and the engineering profession in a manner as exemplary as that of Earll Murman. He has finally (and firmly!) planted himself on the west coast in a well-deserved retirement.

Earll, thank you for all you have done for us and with us. You have done it extremely well. We remain grateful. Be well and return often.

Wesley L. Harris is head of the MIT Department of Aeronautics and Astronautics. He may be reached at [weslhar@mit.edu](mailto:weslhar@mit.edu)

## **AERO-ASTRO**

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## **DESIGN**

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Cover: Graduate students Brett Bethke (left) and Mario Valenti watch as a quadrotor flying  
vehicle they helped develop autonomously makes its way about the Aeronautics and Astronautics  
Department's Aerospace Controls Lab. (Donna Coveney/MIT photograph)