AERO ASTRO

annual 2004-2005

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AERO-ASTRO

Editors

Ian A. Waitz	William T.G. Litant
Professor and Deputy Department Head	Director of Communications
iaw@mit.edu	wlitant@mit.edu

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

Aero-Astro No.2. June 2005. ©2005 The Massachusetts Institute of Technology. All rights reserved.

DESIGN

Design Studio at Monitor
Cambridge, MA 02141
designstudio@monitor.com

Cover: A pair of SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites), micro-satellites designed to fly in formation, float in a zero-g test aboard NASA's micro-gravity aircraft. Monitoring the test are (from left)) Stephanie Chan and Steve Sell of Payload Systems; Edmund Kong of Aero-Astro's Space Systems Lab; Gary Blackwood of the Jet Propulsion Laboratory; and Mark Hilstad, an Aero-Astro doctoral candidate. SPHERES was developed through a three-semester undergraduate Aero-Astro capstone class. Chen, Kong, Blackwood, and Hilstad all hold degrees from MIT Aero-Astro. *See page 1.* (NASA photograph)

The scholarly contributions reviewed in these pages reflect a new Aero-Astro department: one positioned for the future and dedicated to continued leadership in education, research, and service.

Dear colleagues and friends:

We share an immense pride in this department. As we leafed through the galleys of this second annual issue of *Aero-Astro*, we were struck by the expertise, energy, diversity, dedication and leadership of our Aero-Astro community. Turn the pages: you'll read about Dave Miller and his students' fascinating developments in space architecture, Jack Kerrebrock's profound advances in gas turbine design, Nancy Leveson's groundbreaking work to ensure the safety of mission-critical software, and Moe Win's pioneering exploration of ultrawide bandwidth communication. You'll discover how Paul Wooster and Erika Wagner are leading a team that's blending hardware design, biomedical engineering, systems engineering, biology, and management as they strive to be the first student group to orbit and retrieve a mammal-bearing spacecraft. You'll see how Dave Darmofal markedly improved student learning by applying new engineering pedagogy, and how our unique Learning Laboratory has become an model for universities throughout the world that are adopting Aero-Astro's CDIO educational design. Finally, you will read Sheila Widnall's thoughts on her pioneering career as a leader within and outside MIT.

The scholarly contributions reviewed in these pages reflect a new Aero-Astro department: one positioned for the future and dedicated to continued leadership in education, research, and service. We have recently reorganized our five teaching divisions (structures & materials; fluids & propulsion, systems; humans & automation; and information, controls &

estimation) into three interdisciplinary sectors, each under the leadership of one of our most distinguished faculty members. Vincent Chan, the director of MIT's Laboratory for Information and Decisions Systems and a dual appointment with the Department of Electrical Engineering and Computer Science, leads our Information Sector. Daniel Hastings, the Director of the Institute's Engineering Systems Division (holding a dual appointment), leads the Systems Sector. Gas Turbine Lab Director Alan Epstein leads the Vehicles Technology Sector.

We are not resting on our laurels. Although we only recently completed a multiyear implementation of our 1998 strategic plan, we have begun a new process to formally reconsider our mission, our guiding principles, and our strategy. The Institute is poised to enter a new era under the exciting leadership of our new president, Susan Hockfield. And the future of aerospace — and our department — is confronted with major near-term challenges driven by uncertainty in the airline industry and the reduction in federal support of basic aeronautics and astronautics research. Concomitant with these challenges are major opportunities for Aero-Astro. These opportunities include: (1) the conception and design of a more efficient, safe, and secure national airspace system; (2) the conception and design of vehicle technologies, operations and policy strategies to enable increased mobility with decreased impact on the local and global environment; (3) the conception and design of the next generation space communications system; (4) the conception and design of system architecture and physical subsystems supporting robotic and human space exploration; and (5) the conception, design, development, and testing of pedagogies that greatly enhance the effectiveness and efficiency of engineering teaching and learning.

Aeronautics and Astronautics Department Head Wesley Harris and Deputy Head Ian Waitz with the heads of the new Department Sectors: (from left) Daniel Hastings, Systems Sector; Waitz; Harris; Alan Epstein, Vehicle Technologies Sector; and Vicent Chan, Information Sector. This team is ensuring Aero-Astro is positioned for the future and dedicated to continued leadership in education, research, and service. (William Litant photograph)

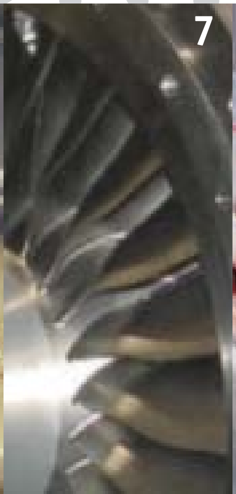
As we wrote in the introduction to the last issue of *Aero-Astro*, we are proud of our past, but our focus is on the future. Again, the articles included here tell the tale of but a small fraction of our research, our teaching, and our people. Please accept our invitation to visit us in Cambridge, meet with us, take a tour, learn more, and, most importantly, let us know your thoughts about this department and how it should address the future. We'd enjoy the opportunity, and we think you will, too. After all, it's hardly a chore to share thoughts about something you believe in — and are truly excited about!

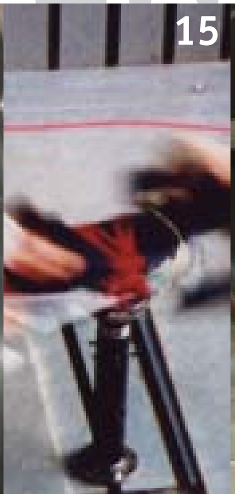
Ian A. Waitz

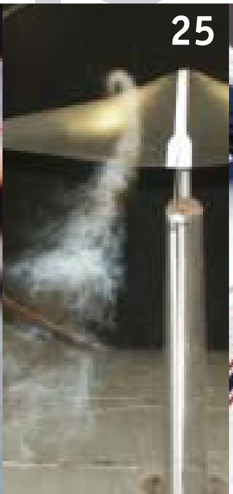
Wesley Harris
Department Head

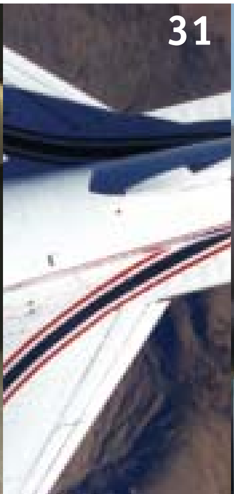
Ian Waitz
Deputy Department Head

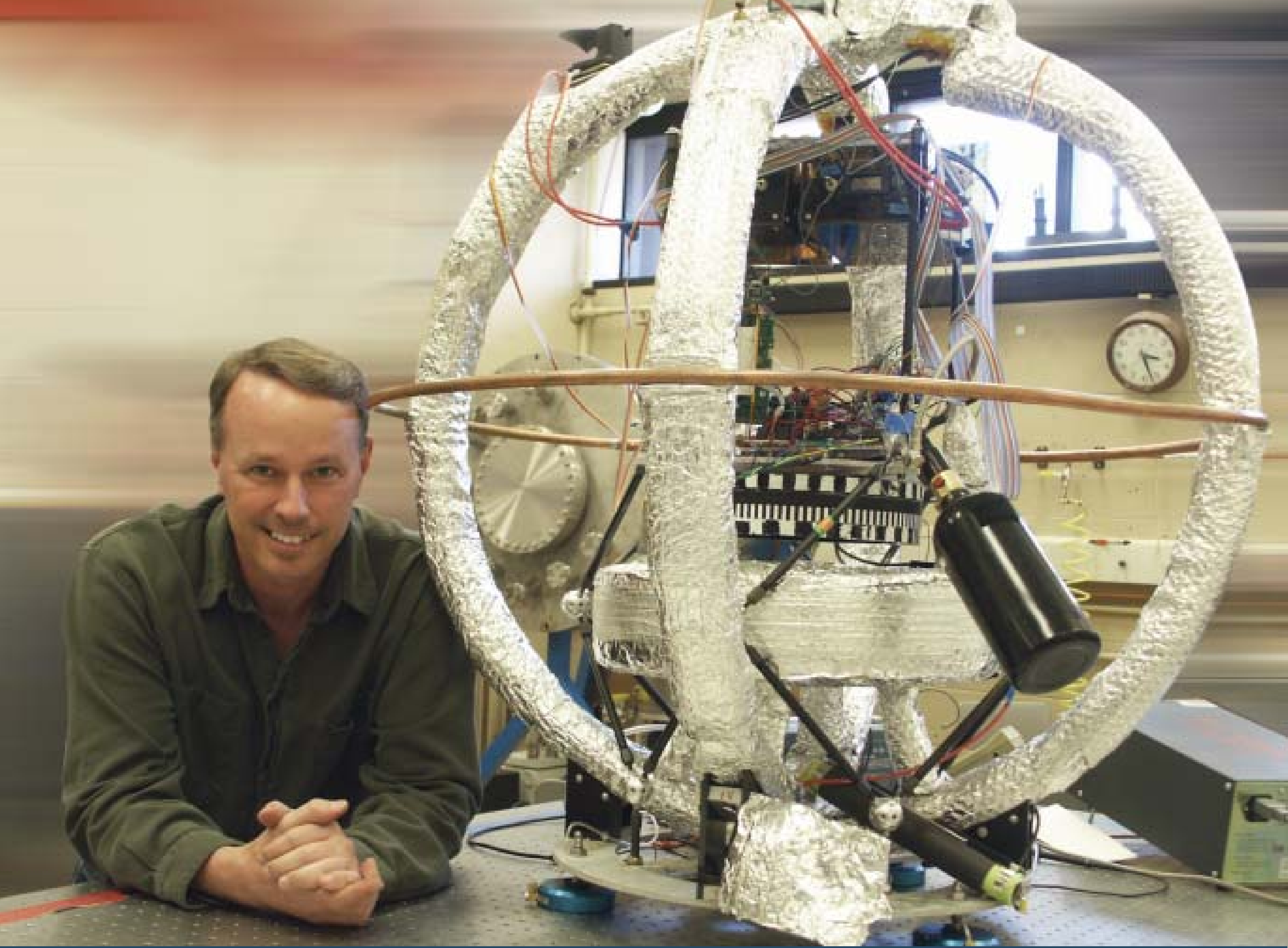
CONTENTS











Dave Miller in his lab with an electromagnetic formation flight testbed. EMFF — spacecraft positioning themselves through magnetic attraction/repulsion of other spacecraft — would use solar energy, obviating a dependence on finite fuel supplies brought with them from earth. (William Litant photograph)

Distributed satellite systems offer vision for
EXPLORATION AND EDUCATION

By David W. Miller

Astronomy has entered a golden age. We are starting to answer the age-old questions: How did it all begin, how will it end, and is there life beyond Earth? Discovering the answers to these questions raises daunting engineering challenges. Space telescopes — our premier investigatory tools — are becoming ever larger, exceedingly precise, and more exotic. Our challenge is to engineer a telescope effectively the size of a football field, that operates in an environment only slightly warmer than absolute zero, orbits 10 million miles from Earth, is accurate to a precision less than the diameter of a hydrogen atom, and which we've never run in this operating environment prior to launch.

The MIT Aeronautics and Astronautics Department's Space Systems Laboratory is developing an innovative approach to satellite design that alleviates drawbacks that have plagued the industry: high design costs, complexity of system integration and validation, risk of large deployment, low reliability due to design customization, and limited design heritage and legacy. By modularizing typical satellite functions (e.g., propulsion, power, attitude control) and achieving subsystem interconnectivity through genderless docking ports, and wireless command and data handling, we simplify assembly and test prior to launch as well as enabling self-assembly and reconfiguration once on orbit. The goal is to reduce the cost, risk, and time required for the deployment of new spacecraft by changing the fundamental methodology used in their development. Most spacecraft are developed as point-designs, optimized for their particular missions. Launch costs are so high and opportunities so rare, that it is only natural for program managers to include as much functionality as possible into each spacecraft. For this reason, most spacecraft are one- or few-of-a-kind creations. While components may be reused from one spacecraft to the next, there is usually a high degree of customization, leading to inevitable increases in testing and verification costs, along with unavoidable decreases in reliability. This customization has several drawbacks. First, each spacecraft requires a substantial upfront design cost. Second, the resulting design lacks the risk reduction associated with flight heritage. Third, subsystem functionality cannot be truly tested until some level of system integration has been performed. Fourth, the designs lack the cost and learning curve savings of large production runs. Fifth, repair of subsystems prior to launch requires substantial disassembly in order to get access. Sixth, on-orbit repair, replenishment, and upgrade of subsystems are not possible.

This need to customize, yet service and upgrade systems can be seen in the field of astronomy. Whether it is the Mount Wilson telescope in California or the Hubble Space Telescope in Earth orbit, dramatic vistas of the universe have been opened through periodic upgrade of the instruments located at the focus. This ability to service and upgrade has clear benefits. However, the cost of such upgrades is enormous, considering that the next generation of space telescopes will operate 10 million miles from Earth at the second Earth-Sun Lagrangian point [L2]. To improve angular resolution (the ability to distinguish between two closely-spaced objects), the Space Interferometry Mission and Terrestrial Planet Finder exploit multiple telescopes that are spread apart. In the case of the latter, these individual telescopes lie on separate spacecraft that are flown in formation.

> **THE COST OF UPGRADES IS ENORMOUS CONSIDERING THE NEXT SPACE TELESCOPES WILL OPERATE 10 MILLION MILES FROM EARTH**

Coordinating the use of multiple satellites to facilitate assembly, servicing, upgrade, and operation of future space-based telescopes is an emerging field. Distributing mission functionality across multiple satellites has the promise of revolutionizing space exploration in general, while also presenting unique challenges. The research program that I am privileged to lead integrates technology development, on-orbit research, mission design, and undergraduate education into a unique approach to make this vision a reality.

TECHNOLOGY DEVELOPMENT

Satellites use propellant to maneuver from one orbit to another, much like an automobile uses gasoline. Formation flying satellites will also need to maneuver in order to keep formation and retarget. Unlike automobiles, these satellites do not have the advantage of maneuvering into a gas station as their propellant runs low. Instead, they must bring with them, at launch, all of the propellant they will need over their lifetime. This makes propellant a precious commodity. Electromagnetic Formation Flight (EMFF), using renewable solar energy, replaces the need for propellant in performing formation flight.

It has been shown both in theory and practice that by using a combination of electromagnetic dipoles and reaction wheels, all relative degrees of freedom among a cluster of vehicles can be controlled without the use of propellant. Using current and future state-of-the-art in high temperature superconducting wire to generate the electromagnetic fields, low power and lightweight systems can be realized that are competitive with current high specific impulse propulsion, but are not life-limited by propellant consumption. Because of the low power requirements and lack of consumables, much more aggressive maneuvers can be performed continuously over the lifetime of the mission. Any mission that can be satisfied by controlling only relative degrees of freedom is a potential application for EMFF. Potential applications include all cluster formation flying (reconfiguration) and formation keeping (fighting perturbations such as differential drag, gravitational variations, and solar pressure), as well as rendezvous and docking.

ON-ORBIT RESEARCH

The SPHERES formation flight laboratory on the International Space Station (ISS) is the culmination of a succession of dynamics and controls research laboratories developed by the Space Systems Laboratory and flown on the Shuttle and ISS. By exploiting platforming concepts where a common chassis with standardized interfaces allows modular components to be added, these laboratories have been extensible in both hardware and software to accommodate a myriad of diverse research objectives. Furthermore, these laboratories are operated in the risk-tolerant shirtsleeve environment where software is not needed as a safety control. This allows the research to push the limits of engineering capability as well as rapidly iterate on design in much the same way as is done in terrestrial research laboratories.

Consider that we formation fly every day on the interstate with surprisingly few collisions. However, we do not toss the keys to our expensive car to our 16-year-olds. Instead, we have them practice in a less expensive car in a risk-tolerant environment (e.g., parking lots) until handling nominal and off-nominal conditions becomes second nature. The goal for satellite formation flight, rendezvous, and docking is to show that it is not only feasible but also robust. SPHERES provides exactly that environment for formation flight and on-orbit assembly.

Funded primarily by the Defense Advanced Research Projects Agency's Orbital Express, SPHERES is a multi-satellite docking laboratory designed to mature metrology, autonomy, and path-planning algorithms for autonomous rendezvous and docking in the risk-tolerant yet long duration micro-gravity environment inside ISS (http://ssl.mit.edu/spheres). Uplinking software, downlinking data, and attaching payloads to the SPHERES expansion ports facilitates spiral algorithm development and hardware extensibility. Five flight-qualified SPHERES have been built, three of which are, at this writing, awaiting launch after Shuttle return-to-flight.

MISSION DESIGN

For monolithic telescopes, the cost of the primary mirror grows faster than its area. This has led designers of future systems to consider sparse apertures to achieve the fine angular resolution associated with a large telescope. Sparse apertures combine the light from multiple smaller telescopes to achieve this effect. The modularity inherent in a sparse aperture can then be exploited throughout the spacecraft to embody the functions of assembly, servicing, upgrade, and operation. To quantify the attributes of modular telescope design, the Space Systems Laboratory developed the Adaptive Reconnaissance Golay-3 Optical Satellite (ARGOS) to quantify the savings associated with building a sparse aperture primary, the additional cost of providing the beam train that combines the light from the multiple apertures to the requisite precision, and the system scale at which such an architecture becomes favorable over monolithic systems such as the Hubble Space Telescope. The data clearly show that modular optical systems are more cost-effective than monolithic systems for larger telescopes, based purely on fabrication costs. When one also considers the opportunities for assembly and servicing that modularity provides, such architectures hold the promise of revolutionizing the next generation of space telescopes.

UNDERGRADUATE EDUCATION

To extend the design-build experience beyond graduate students, staff and subcontractors, the SPHERES, ARGOS, and EMFF prototypes were developed through a three-semester undergraduate Aero-Astro capstone class developed as part of the Department's CDIO Initiative (http://www.cdio.org); an innovative educational framework that stresses engineering fundamentals set in the context of Conceiving—Designing—Implementing—Operating real-world systems and products. As an alternative to conventional design and laboratory classes, the integrated design-build sequence allows the students to take a concept through design, fabrication and testing and thereby gain a working knowledge of the engineering lifecycle. Furthermore, while working on their specific subsystems in small teams, the students also contribute to team-wide activities such as requirements formulation, design reviews, system integration, and field testing. Indeed the very first spheres were designed, developed, fabricated, and flown by undergraduates on NASA's KC-135 Zero-Gravity Simulator aircraft. Not only does this innovative educational environment enrich the experience of the undergraduates, it also provides an advance rapid prototyping team supporting my graduate research program. The numerous follow-on research programs funded by government and industry testify to the merit of integrating undergraduate education with cutting-edge research.

WORKING IN SMALL TEAMS, STUDENTS CONTRIBUTE TO REQUIREMENTS FORMULATION, DESIGN REVIEWS, SYSTEM INTEGRATION, AND FIELD TESTING

The research activities within the Space Systems Laboratory address all aspects of the engineering lifecycle of space telescopes from systems architecture, to development of enabling technology, to on-orbit technology maturation. The goal is to develop new engineering practices that help the next generation of space telescopes keep pace with the new scientific questions arising.

David W. Miller, director of the Space Systems Laboratory, is an associate professor in the MIT Department of Aeronautics and Astronautics. He may be reached at millerd@mit.edu.

An MIT-designed high-ratio fan installed for testing at NASA's Glenn Research Center. The tests confirmed the viability of aspirated compressors in a simulated engine environment.

MIT-designed aspirated compressors = shorter, lighter engines: A BOON FOR SUPERCRUISING JETS

By Jack L. Kerrebrock

Gas turbine engines are, in theory, simple. They comprise three main parts: a compressor for squeezing incoming air; a combustion chamber for burning fuel, producing high-pressure and velocity gas; and a turbine that extracts some of the power from the flow to drive the compressor. In the following article, Professor Emeritus Jack Kerrebrock provides a brief non-technical view of the research on aspirated compressors, historical and ongoing, at the MIT Aeronautics and Astronautics Department's Gas Turbine Laboratory.

By aspirated compressors we mean a class of compressors in which the flow is improved by extracting a small fraction of low-energy flow at locations where its accumulation would decrease the pressure rise and increase in losses by deviating the main flow from the intended path. In axial flow compressors these locations typically are on the low-pressure surface of the blades, just ahead of the deceleration of the flow toward the trailing edge, at points of shock impingement, and in corners where the blades join the inner and outer casings of the flow path.

A principal advantage of aspirated compressors is that they require fewer stages compared to competitive non-aspirated designs. This enables shorter, hence lighter, engine designs, which are especially attractive for aircraft that cruise supersonically. Supersonic aircraft tend to have high fuel consumption relative to subsonic aircraft, so the fixed weight is very critical.

To assist the uninitiated in following the discussion, a few points of context may be helpful. First, we are mainly interested in compressors such as those used in the inlet portion of aircraft engines, including the fans and the initial stages of core compressors. The flow is generally axial and transonic, meaning that the speed of the rotating blades, and, hence, the relative flow velocity, is in the range from just below to just above sonic. This is a result of two facts of nature: first, the fractional temperature rise of the flow through the compressor varies as the square of the blade speed, placing a premium on higher blade speeds; second, as the flow becomes supersonic, shock waves can form, causing entropy increases that lower the efficiency of the compression process. Entropy increases imply losses in total pressure and reductions in engine efficiency. Since these losses increase rapidly with Mach numbers exceeding unity, the designs tend to optimize with Mach numbers relative to the blades ranging from a minimum of about 0.8 at smaller radii to a maximum of 1.5 near the tips of the rotating blades. This has led to the characterization of such compressors as "transonic." A third fact of nature is that in this (transonic) range of Mach number, the mass flow per unit of stream tube area varies slowly with Mach number (peaking at M = 1), so that a small variation in the area of a flow stream tube can result in a relatively large variation in Mach number or velocity. This variation can be smooth and lossless, or it can be abrupt if due to shock waves. It follows that the development of low-speed flow regions on the blade surfaces, even though confined to thin boundary layers, can have strong effects on the flow through the compressor blading.

ONLY RECENTLY HAVE DESIGN TOOLS BEEN DEVELOPED THAT ENABLE DESIGNERS TO TAKE ACCOUNT OF SUBTLE GEOMETRIC VARIATIONS OF THE COMPRESSOR FLOW PATH

Aspiration — removal of the boundary layer fluid — allows local modification of the available flow area and the shock wave structure. It can be a powerful tool for enabling higher pressure rise in both the rotating and the stationary blades of compressors. It is this potential that we seek to exploit in our aspirated compressors.

INITIAL DEVELOPMENT

These general ideas have long been understood within the small community of compressor designers. However, it is only recently that design tools have been developed that enable the designer to accurately take account during the design process of the effects of subtle variations in the geometry of the compressor flow path, and of the interactions of the stream tubes as they pass through the blading. The first step toward this capability came with the development of computational fluid dynamic techniques capable of dealing with transonic flows. But, these were initially analysis techniques, capable of describing the flow through passages of prescribed geometry. They were not very useful for compressor design, the objective of which is to find a geometry that will yield a flow field of a desired character. The desired character includes the rate of pressure rise on the low-pressure (suction) surface of the blade, shock locations and strengths, and other features that control the pressure rise through the blades, and the losses that determine the efficiency of the compressor.

The next important step came in the 1980s with the development of the MISES design approach by Aero-Astro Professor Mark Drela and master's candidate Harold Youngren. In this approach the flow is divided into a set of interacting stream tubes, two being the boundary layers on the blade surfaces, and several describing the inviscid flow between them. It is capable of describing the response to quite subtle variations in blade shape, with modest computing requirements. Equally important to the discussion, it is capable of accurately representing the effect of aspiration on the flow, as mass flow reduction occurs in the stream tube adjacent to the point of aspiration.

At about the same time as the development of MISES, this author and his students embarked on experimental efforts to demonstrate the efficacy of aspiration in transonic compressors. The first serious attempt was by doctoral student Duncan Reijnen, who added aspiration scoops to the suction sides of several blades of an existing transonic compressor. This yielded positive effects, but was limited from the outset by the fact that not all blades had aspiration. Clearly, the next step was to develop and

Jack Kerrebrock in the MIT Gas Turbine Lab with a prototype aspirated compressor. (William Litant photograph) test a stage in which it would be possible to fully exploit the advantages of aspiration by designing for a higher pressure ratio than would be possible with aspiration.

FULLY ASPIRATED STAGES

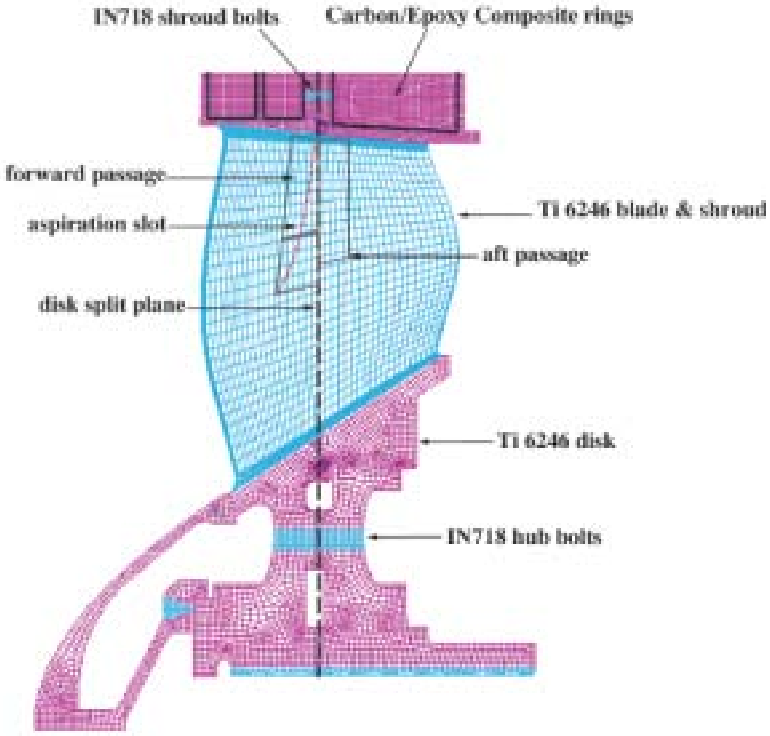
Support was obtained from the Air Force Office of Scientific Research to undertake the design and test of a fan stage, with a pressure ratio of about 1.6 at a tip speed of about 750 ft/s. (For non-aspirated stages, a speed of about 1300 ft/s would be required to give this pressure ratio.) Dr. Ali Merchant, an Aero-Astro research engineer who had worked with Mark Drela, undertook to modify MISES to meet the needs of the turbomachinery geometry and to carry out the aerodynamic design. MISES had previously been used mostly for external aerodynamics. Brian Schuler undertook the construction of the stage and its test in the MIT blowdown compressor as his Ph.D. thesis.

Shortly after the initiation of this work, we were fortunate to receive support from the Defense Advanced Research Projects Agency for an accelerated and expanded program as part of its MAFC (Micro Adaptive Flow Control) program, under the enlightened management of Dr. Richard Wlezien. This included more money for the low tip speed fan, and substantial funding for a very ambitious high-pressure ratio fan, to be designed and built by MIT and tested at NASA Glenn Research Center. After some preliminary calculations, the design pressure ratio was set at 3.5 at a tip speed of 1,500 ft/s. The speed is typical of first stages in engines, but the pressure ratio would normally be below 2. To add credibility to the work and speed it along, collaboration was sought and received from Pratt & Whitney in the design phase, and from Honeywell Aircraft Engines in the mechanical design.

THE HIGH PRESSURE RATIO STAGE DEMONSTRATED THE VIABILITY OF ASPIRATION IN A SIMULATED ENVIRONMENT

Both of these stages were conceived as critical tests of our capability for designing stages to capture the potential advantages of aspiration. The low tip speed stage should be viewed as a test of the viability of the MISES-based design system, free of mechanical challenges because of the low stress, short time environment of the blowdown compressor. The high-pressure ratio stage was a more severe test of the aerodynamic design and also a test of the viability of aspiration in a high speed stage suitable for use as the first stage in an engine. Both rotors were designed with shrouds at the tips, to minimize the aerodynamic limitations due to tip clearance leakage, and also to provide a simple means for removal of the aspirated flow from the rotor. This flow was transferred outward in the blade, collected in the shroud, and transferred to a peripheral collection manifold.

The benign environment of the blowdown compressor made it possible to form the suction passages in the rotor of the low tip speed fan by means of cover plates attached mechanically over cavities machined into the aluminum rotor. This was not feasible for the high-pressure ratio rotor and stator, so they were each assembled from front and rear halves, the suction passages being machined into the halves from the parting surface. This construction is shown in the illustration to the right. Because of the high tip speed, it was necessary to support the shroud of the high-pressure ratio rotor with a graphite/epoxy circumferential winding, also shown in the drawing. In itself, this mechanical arrangement offers some interesting tales, but they will be dispensed with in consideration of their rather arcane appeal.



High-pressure ratio rotor construction

Both of these stages met their design objectives, producing their respective design pressure ratios and mass flows at design speed. They therefore provide two distinct validations of the MIT/NASA design and analysis system for aspirated stages. The high-pressure ratio stage in addition demonstrated the viability of aspiration in a simulated engine environment. It was possible to explore the flow in the low tip speed fan in some detail, and the results are documented in Schuler's Ph.D. thesis and in a publication. Cost and schedule pressures prevented exploring the flow in the high pressure ratio stage as fully as we would have liked, so we have had to settle for the fact that “it worked.” In any case, it provided a solid basis for further exploration of aspirated compressors.

ONGOING WORK — COUNTER-ROTATION

With the success of these two aspirated stages, we sought to expand the verified design space to include multiple stages. A possibility that offered new challenges, and was enticing to Aero-Astro Professor Alan Epstein, Merchant, and this author, was a pair of counter-rotating stages. The principal advantage of counter-rotation is that swirl from the first stage augments the work capacity of the second, so that a compressor made up of two counter-rotating rotors, without stators, can be shorter and lighter than a two-stage co-rotating compressor. Such an arrangement can have additional advantages associated with the turbine stages required to drive the two compressor rotors. In the applications envisioned for such an arrangement, tip shrouds are not viable because of the high temperature, so the aspirated flow from the rotors must be exhausted inward, rather than outward as was done in the first two stages. This presented additional challenges to the design system.

This proposition was attractive to DARPA, which is funding a program to design, build, and test a counter-rotating two-stage compressor in the blowdown mode at MIT. Dr. John Adamczyk of NASA Glenn has participated in the analysis of the design. As of this writing, the apparatus for this experiment is being assembled. Dr. Gerald Guenette, a principal research engineer in the Gas Turbine Lab, has the lead for the experiment, while Merchant has carried out the design. Epstein is in charge.

POSSIBILITIES FOR THE FUTURE

As noted at the beginning of this article, aspirated compressors have fewer stages compared to non-aspirated designs making possible lighter engines designs, which are a plus for supersonic-cruising aircraft. This is because they tend to have high fuel consumption relative to subsonic aircraft, so the weight is very critical. Ali Merchant has now proposed a design that combines a short supersonic diffuser with a supersonic inflow, subsonic outflow fan. This design would make possible a compression system about half the length and weight of a conventional design, in which the flow is diffused to subsonic speed, and then taken into the engine.

This arrangement poses new challenges to our design system. We look forward to addressing these challenges in coming years.

Jack L. Kerrebrock, Professor Emeritus of Aeronautics and Astronautics, served on the MIT faculty from 1960 to 1996. He was head of the Aeronautics and Astronautics Department from 1978 to 1981 and from 1983 to 1985, Associate Dean of Engineering from 1985 to 1989, and Acting Dean from 1989 to 1990. A National Academy of Engineering member and an Honorary Fellow of the American Institute of Aeronautics and Astronautics, Kerrebrock's research activities have focused on propulsion and power generation. He may be reached at kerbrock@mit.edu.

The Gerhard Neumann Hangar, part of Aero-Astro's Learning Laboratory, offers space for the construction and testing of larger objects, like this human-powered centrifuge designed to offer exercise and artificial gravity in a zero-g environment. (William Litant photograph)

Learning in a
LANDMARK LABORATORY

By William T.G. Litant

Aero-Astro's Learning Laboratory encourages students to conceive, discover, and build.

Senior Chris Sequeira was deep into his 16.62X Experimental Projects course when the practical value of the Aeronautics and Astronautics Department Learning Laboratory's unique design suddenly became clear. "Anyone who studies in this space has all the resources he needs right here," he realized.

Sequeira was constantly popping back and forth — from a terminal in the Design Center, down the steps to the library to check a reference, stepping through a door into the large communal space to confer with fellow students, dropping down a level to punch coordinates into a computer numerically controlled milling machine. "Everything is just a couple of steps away from everything else," he says enthusiastically.

Sequeira's revelation is hardly unique — many of his Aero-Astro peers share it. What is not as overtly obvious to the students is that this unique blend of workspaces and thinkspaces was created specifically to compliment the department's landmark educational program for producing the next generation of engineers: the CDIO Initiative.

THE CDIO INITIATIVE

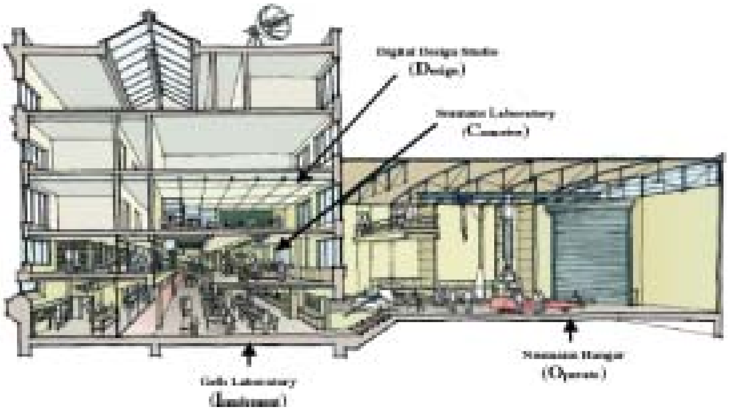
Before we examine Aero-Astro's Learning Lab, it's helpful to understand the CDIO rationale that drove its implementation.

In recent decades, engineering education and real-world demands on engineers drifted apart. We in Aero-Astro identified a need to close this gap. To do this, we conceived and developed a new vision. The CDIO Initiative is the embodiment of that new vision. A CDIO education stresses engineering fundamentals, set in the context of the conceiving—designing—implementing—operating process that engineers use to create systems and products. The CDIO Initiative is rich with student projects complemented by internships in industry. It features active group learning experiences in both classrooms and in Aero-Astro's new learning workshop/laboratory.

We began our development of CDIO in the late 1990s. The first task we shouldered in designing our new educational program was compiling a list of the abilities needed by engineers. To do this, we formed focus groups of industry representatives, engineering faculty and other academics, university review committees, and Aero-Astro alumni. We asked the focus groups, "What are the knowledge, skills and attitudes that the graduating engineer should possess?" We melded the focus group results with industry and educators' wish lists and created the first draft of a new syllabus (the outline of topics of study). The top levels of our syllabus match what we have determined are the essential functions of an engineer: mature and thoughtful individuals who understand how to "conceive, design, implement and operate complex value-added engineering systems in a modern team-based engineering environment."

The next task was to change the Aero-Astro curriculum to meet our learning goal. We modified the curriculum to include design–build projects. We coordinated and linked conventional subjects to demonstrate the interdisciplinary nature of engineering. And, we created a capstone course: a challenging, culminating experience where students design, build, and operate a product system.

This elevation of the Learning Laboratory indicates areas designated for support of conceiving, designing, implementing, and operating — the four main elements of the Aeronautics and Astronautics Department's syllabus. (Cambridge Seven Assoc. illustration)



WORKSPACES KEY TO THE LEARNING ENVIRONMENT

Engineers design and build systems and products. In the CDIO Initiative, workshop and laboratory experiences support the theory-to-practice progression. Experiences in conceiving, designing, implementing and operating are woven into the curriculum. Workshops and laboratories — we call them workspaces — are key to the CDIO learning environment. They must support a number of the modes of active and hands-on learning including experimentation, social interaction, team building and team activity.

Since conceiving, designing, implementing and operating is the context of the Aero-Astro education, we want to provide workshops and lab environments organized around C, D, I, and O.

BEHIND THE NAME:
The Robert C. Seamans Jr. Laboratory

On a number of levels, it's fitting that Bob Seamans' name is associated with the Aero-Astro Learning Lab. "I came to MIT in the early '40s," he reminisces. "I did my thesis work on vibration equipment. I did my work in Building 33 right under what today is the Learning Laboratory. I can't be more excited than to have that complex named for me — I never anticipated it!"

Seamans is particularly pleased his name is associated with a student workspace. "When I was a student, I took two courses with Doc Draper," Seamans says, invoking the name of the legendary former Aero-Astro head and founder of Draper Lab. "Doc would say, 'You can't learn to throw a baseball by reading about it.' Now, I, too, am a great believer in the value of hands-on learning." He is particularly impressed at the way some of the facilities, such as the Concept Forum and Design Room, are designed to replicate those found in industry. "This gives the students a valuable real-life experience. I've spent many hours in rooms like those," he says.

Seamans emerged from Harvard University in 1939 with a B.S. and then headed down Mass. Ave to MIT where, in 1942, he received his M.S. in Aeronautics, and in 1951, his Sc.D. in Instrumentation. He completed a graduate executive program in business administration at Columbia University in 1959. Between 1941 and 1955 he was successively an instructor, assistant professor, and associate professor in MIT's Department of Aeronautical Engineering, also working as a project leader in the Instrumentation Lab, chief engineer for Project Meteor, and a director of the Flight Control Lab. Seamans joined RCA in 1955. Between then and 1960 he managed and was chief engineer of the company's Airborne Systems Lab, and was Missile Electronics and Controls Division chief engineer. From 1957-62, he was a member of the Air Force's Science Advisory Board

In 1960, Seaman's left Massachusetts for Washington where he started a nine-year career with NASA as associate administrator, deputy administrator, and then a consultant to the administrator. In 1968 he returned to MIT as the Jerome Hunsaker Visiting Professor. From 1969-73, Seamans was Secretary of the Air Force. He was president of the National Academy of Engineering from 1973-74, and was Energy Research and Development Administration Administrator from 1974-77. He returned to MIT in 1977, where he held the Luce Professorship until his retirement in 1984, and served as Dean of the School of Engineering from 1978-81. Following his retirement, he served as a senior lecturer in the Aeronautics and Astronautics Department from 1984-96.

His accomplishments include attaining the position of director of the Charles Stark Draper Laboratory. He is a trustee of the Boston Museum of Science, the Woods Hole Oceanographic Institute, and the Carnegie Institution. Seamans' list of awards and honors is substantial and includes honorary degrees from eight universities.

Seamans makes regular appearances on the MIT campus, often lecturing to Aero-Astro classes. He was closely involved with the development of the Learning Lab, never realizing during the process that it would eventually bear his name.

Laurence Young, MIT's Apollo Program Professor, is Seamans' close friend. "Bob represents the ideal of education and service, having spent his life bouncing from teaching to running major government programs," says Young. "He's shown amazing imagination and talent, particularly in his work in the Apollo Program and his service to the Air Force. The Seamans' Lab is a very fitting testament to his dedication to education."

Seamans sums up his feelings about the Lab in a simple statement, "When I see students working there, I'm thrilled."

THE LEARNING LAB

Since 1928, Aero-Astro has been located in the Guggenheim Aeronautical Laboratory, MIT Building 33, which is a traditional university structure containing traditional offices, classrooms, and labs. With the advent of our educational model, we needed to facilitate CDIO with a complimenting learning environment, rethinking and redesigning our space, equipment, and operations.

The rehabilitation of our venerable home was initially conceived as a partial renovation. However, the adoption of the CDIO paradigm inspired broader, more innovative measures. The project grew to include all four floors, relocation of the library to a central location, a major addition for large-scale projects, and a central exhibit gallery on MIT aerospace history and technology.

To develop our project, then Department Head Professor Edward Crawley brought in the renowned Cambridge Seven Associates architectural firm and C7A architects Peter Kuttner and Steve Imrich. Crawley, Kuttner, and Imrich assembled a group of faculty, staff, students, architects, education specialists, and contractors, who would develop the Learning Lab as a team.

We determined that our new environment would compliment CDIO with areas for conceiving, areas for designing, areas for implementing, and areas for operating. Specifically:

- *Conceive* spaces would allow students to envision new systems, understand user needs and develop concepts. These spaces would emphasize reflection and reinforce human interaction. They would be linked with library resources, and have sufficient technology for communications and information retrieval.

- *Design* spaces would support the new paradigm of cooperative digitally supported design. They would allow students to design, share designs, and understand interaction. They would include a central room for large group interaction, and be connected to breakout rooms for smaller teams to work on their projects. They would be IT-rich and in proximity to build space, reinforcing the design-build connection.

- *Implement* spaces would allow students to build small, medium, and large systems. They would offer mechanical, electronic and specialty fabrication, all visible to other students and visitors. They would offer opportunities for software engineering and integration. A key element (and challenge) would be to make them safe, yet accessible as much as possible outside the traditional school hours.

- *Operate* spaces would create opportunities for students to learn about engineering operations. There, they could operate their experiments and projects and simulate operations of real systems. In addition, operate spaces would eventually offer digital linking to real systems.

We also know that needs change and that use is not always predictable, so our spaces had to be flexible to accommodate evolution.

The result of our endeavors was the $15 million renovation of the building as our award-winning multistory Learning Laboratory, designed to closely integrate with curriculum and pedagogy. Applying lessons of the workplace to the academic setting, we created a physical environment supporting our mission, our productivity, and, not incidentally, recruitment of top student, faculty and administrative talent.

BEHIND THE NAME:

The Arthur and Linda Gelb Laboratory

The Gelb Laboratory, named for Aero-Astro alumnus Arthur Gelb and his wife Linda, a one-time MIT reference librarian, is where students reap much of their experiential learning. "Linda and I both feel that MIT is an extraordinary place," says Gelb. "When I arrived at MIT the buildings were built, the faculty was in place, and the course curricula were established. Clearly, people I will never know paved the way for my extraordinary experience at the Institute."

Gelb's engineering career began in 1956 when the City College of New York student began a series of jobs with the American District Telegraph Company, Westinghouse Corp, and (as a graduate) the Charles Stark Draper Laboratory. In 1959 he earned an M.S. in Applied Physics at Harvard University. By 1961 he was holding a multi-disciplinary MIT Sc.D. in Instrumentation (what today we call Systems Engineering). From 1961-66 he was a manager of systems analysis at Dynamics Research Corporation. He left DRC to co-found The Analytic Sciences Corporation (TASC), an applied information technology firm specializing in intelligence and advanced navigation, guidance and communication systems for national defense, civilian weather data distribution, and power utility software. Gelb sold TASC in August 1991, and it is now part of Northrup Grumman Corporation. Today, Gelb is president of Four Sigma Corporation in Lexington, Massachusetts, a firm that develops mathematical, computer-based trading methods for its own private hedge fund.

Gelb is the co-author of two books and approximately 30 technical journal articles. In 1969 he received the CCNY Outstanding Young Engineer Award. From 1975-77 Gelb served on the Governor's Management Task Force, addressing the efficiency of state government in Massachusetts. In 1976, he was appointed to a seven-year term on the Massachusetts Port Authority board, eventually completing his term as vice chairman. He subsequently spent seven years on the Massachusetts Board of Regents of Higher Education.

In 2002, Gelb was named to a special Massport committee created in the wake of 9/11 to advise the Authority on security technologies. That same year he was elected an MIT Corporation Life Member. Gelb has chaired the Aero-Astro Visiting Committee, and is on visiting committees for Electrical Engineering and Computer Science, Media Laboratory, Brain and Cognitive Sciences, and the Engineering Systems Division. He chairs the latter.

Aero-Astro Professor Edward Crawley, who led the development of the Learning Labs, says of Gelb, "Art's life and his work offer a superb example for our students of the benefits of applying the systems approach to engineering and enterprise, the basis of our department's educational structure. Art has done an outstanding job of melding an MIT education, an innate understanding of technology, and incredible business acumen to build a successful company and contribute to our nation's security and defense. It's certainly fitting that we pass under his name each time we enter the lab."

Gelb says. "My way was paved by others. It is my privilege to have been able to repay that debt, in part, by helping to create the wonderful Aero-Astro teaching laboratories, one of which bears the Gelb family name, in anticipation of the next generation of MIT students."

BEHIND THE NAME:
The Gerhard Neumann Hangar

Gerhard Neumann, who the Cincinnati Enquirer once referred to as "a feisty engineering genius," is the man credited with launching General Electric into the jet engine business. Born in Germany in 1917, he received an engineering degree from Mittweida Ingenieurschule in Saxony. During World War II he joined Claire Chennault's Flying Tigers. When the United States entered the war Neumann was inducted into the Army Air Corps as a staff sergeant, despite still being a German citizen. His reverse-engineering of a Japanese Zero from captured parts was of great assistance to the Air Corps in fighting the plane. He then carried out several missions for the Office of Strategic Services. In 1945, a special congressional act made Neumann a U.S. citizen.

In 1947, Neumann then accepted a job with an airline Chennault was starting in China, which helped to supply the Nationalist forces in the Chinese Revolution. Fleeing China in 1947, Neumann and wife Clarice drove from Bangkok to Jerusalem in a vehicle Gerhard had assembled from two broken jeeps.

Neumann was hired by General Electric in 1948 and became a leading developer of jet-engine technology. The variety of his projects was substantial — from building the first nuclear aircraft engine to heading the design of the famed J79 of which more than 17,000 were produced. His innovations are credited for the company's capturing 85 percent of the world's jet engine business.

In the 1970s, Neumann, as head of GE Aircraft Engines, worked with René Ravaud of the French conglomerate Snecma in a partnership to develop commercial turbofan engines. This partnership led to the founding of CFM International, a joint venture of GE and Snecma. The product of this joint venture, the CFM56 turbofan engine, is still the predominant jet engine.

Neumann won many U.S. and international awards. Among the most notable were the Collier and Wright Brothers Memorial trophies, the Guggenheim and Otto Lilienthal medals, and the Goddard Award. He passed away in 1997.

Neumann's wife Clarice, a former Justice Department attorney, says that her husband would have been "overwhelmed and gratified" to know that MIT aerospace students would be building projects in a teaching lab that bears his name. "He said his most valuable experience was gained when he was an apprentice automobile mechanic at his first job in Germany," Ms. Neumann says.

"He wasn't a foe of theory, but he believed hands-on is the most effective means of learning — actually feeling the metal," says Mrs. Neumann.

THE FOUR ELEMENTS OF THE LEARNING LAB

The Learning Lab comprises four main areas.

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

- *The Concept Forum* — a multipurpose room for meetings, presentations, lectures, videoconferences and collaboration, distance learning, and informal social functions. In the Forum, students work together to develop multidisciplinary concepts, and learn about program reviews and management. From here, students collaborate in real time and across distances with students at other universities, as well as engineers in industry and government.
- *Two Project Offices* — team-focused work and meeting spaces, which may be assigned to teams for weeks or months, or kept available as needed. These rooms support individual study, group design work, online work, and telecommunication.
- *Network Operations Area* — supports learning about the operations and management of networks, a new focus within the department. Examples of its use include student operation of a communications network, and emulation of air traffic control and data flow networks.
- *Seamans Aerospace Library* — a collection of aerospace engineering resources with extensive digital information storage and retrieval capability. The library is

integrated into the learning process and provides students with experiences to develop habits and skills for lifelong learning.

- *Al Shaw Student Lounge* — a large, open space for social interaction and operations, as well as academic support offices.

Arthur and Linda Gelb Laboratory. Located in the building's lower level, the Gelb Laboratory includes the Gelb Machine Shop, Instrumentation Laboratory, Mechanical Projects Area, Projects Space, and the Composite Fabrication-Design Shop. The Gelb Laboratory provides facilities for students to conduct hands-on experiential learning through diverse engineering projects starting as first-year students and continuing through the last year. The Gelb facilities are designed to foster teamwork with a variety of resources (e.g., machining tools, electrical instrumentation, composites) to meet the needs of curricular and extra-curricular projects.

FACILITIES ARE DESIGNED WITH A VARIETY OF RESOURCES THAT FOSTER TEAMWORK

Gerhard Neumann Hangar. The Gerhard Neumann Hangar is new construction added to the rear of the Building 33. It's a high bay space with an arching roof. This space lets students work on large-scale projects that take considerable floor and table real estate. Typical of these projects are planetary rover vehicles, a human-powered zero-g centrifuge, and a hovercraft. The structure also houses low-speed and supersonic wind tunnels. A balcony-like mezzanine level is used for multi-semester engineering projects, such as the experimental three-term senior capstone course, and is outfitted with a number of flight simulator computer stations.

Digital Design Studio. The Digital Design Studio, located on the second floor, is a large room with multiple computer stations arranged around reconfigurable conference tables. Here, students conduct engineering evaluations and design work, and exchange computerized databases as system and subsystem trades are conducted during the development cycle. The room is equipped with multiple video projection systems, distance communication devices, whiteboards, and other information technologies that facilitate teaching and learning in a team-based environment. Adjacent and networked to the main Design Studio are two smaller design rooms: the AA Department Design Room and the Arthur W. Vogeley Design

Room. These rooms are reserved for the use of individual design teams and for record storage. The department's IT administrator occupies an office adjacent to the Design Center, positioning him for convenient assistance.

COMMUNICATION, INTERACTION, COMPETITIVE ADVANTAGE

As student Chris Sequeira discovered, we've taken traditionally separate activities and compressed them in smaller, yet open, spaces that foster interaction. Students and faculty move from shop to classroom, from project area to breakout room, from technology-minimal human interaction spaces to high-tech media room offering real-time interaction with remote facilities around the globe. Essentially, the Learning Lab represents a mini-company, compressed with clarity. Spaces such as the Project Design Room replicate specific industrial facilities, offering students real-world experiences. And, the Hangar offers a place where large-scale projects, such as hovercraft and launch vehicles, can be developed onsite as integral elements of the learning experience.

Unlike the time-honored secluded warrens of research, the Learning Lab is an attractive learning tool for donors, corporate sponsors, potential students, and faculty. Visitors enter from the lobby to experience an open balcony backed by a glass-walled library. From the balcony, they look across to a common often brimming with students working individually and in groups as they pour over projects and assignments. A descending staircase surrounded by a large, open well offers both view and connection to shops and workspaces below. Graphics and artifacts around the balcony/hallway tell the story of Aero-Astro and its leading role in the history of aerospace engineering.

INTERNATIONAL SIGNIFICANCE

It wasn't long following its 2001 completion that the Learning Lab began racking up awards, among them: *Contract* magazine's Educational Facilities Award, American Institute of Steel Construction national merit award, American School & University special citation, School Construction News and Design award for innovative learning. Word spread to engineering schools universities throughout the world that are in the process of constructing new learning spaces and labs, or refurbishing older facilities. Faculty and administrators from Australia, the United Kingdom, South Africa, Scandinavia, Asia, and other parts of the world flocked to the space armed, with notebooks and cameras, to capture the unique process that melded our syllabus and curriculum with our bricks and mortar.

Crawley sums up the project thusly: “The new space upholds our cultural values and assertions that building things is important, and that good ideas come from people talking with one another. It provides exactly what we had hoped: a flexible, interactive environment where students can conceive, discover, and build.”

Is it perfect? Well, Sequeira does have a complaint. He and his colleagues revel in the fact that most of the Learning Lab is accessible 24 hours a day; it’s not all that odd to stroll through the spaces in the wee hours and discover a group huddled around a terminal or a couple of students assembling the frame of a radio-controlled aircraft. But, the Gelb Lab’s Machine Shop, with its comprehensive array of milling machines, lathes, water-jet cutter, and other potentially dangerous equipment, must close when the technical instructor leaves for the day. “Now, if I could only get in there in the middle of the night …” he sighs.

……

Some of the material used in this article appears in more detail in the paper “Engineering the engineering learning environment,” by E. Crawley, C. Hallam, and S. Imrich. The paper was presented by Crawley at the 2002 SEFI Annual Conference in Florence and is available by contacting the European Society for Engineering Education.

William T.G. Litant is the MIT Aeronautics and Astronautics Department Communications Director and the Collaboration/Communications Director of the CDIO Initiative. He may be reached at wlitant@mit.edu.

Aero-Astro senior Christopher J. Sequeira performs a flow visualization in the Wright Brothers Wind Tunnel to detect separated flow over a blended-wing body aircraft model. A project-based approach to learning, such as this, offers students an immediate opportunity to apply theory to problems approaching the complexity of modern aircraft. (William Litant photograph)

Students react to more effective teaching:
CHANGING THE PEDAGOGY

By David L. Darmofal

While the days of the solitary professor lecturing in a cloud of chalk dust (or a blur of viewgraphs) are not gone, a noticeable change is occurring in the engineering classroom. Although some aspects of this evolution are due to technology, many of these changes are the result of continued progress in the understanding of how we learn. Educational research has led to the recognition of a number of principles of effective teaching that we're applying in our classrooms.

The MIT Aeronautics and Astronautics Department is a world leader in engineering education innovation. The Department's 1998 strategic plan recognized the need for changing not only what we teach but also how we teach. Since that time, I have been actively involved in reforming the pedagogy in the courses I teach. Perhaps to no surprise, I've observed that our students recognize the potential for effective pedagogy even when hampered with an initially poor implementation. And, when well implemented, our students find the new pedagogy highly effective.

CHANGING PEDAGOGY

One of the subjects I teach is 16.100 Aerodynamics. 16.100 is a junior/senior-level course with a typical enrollment of around 40 students. While not required, it's one of a handful of courses from which Aero-Astro students may select to fulfill their undergraduate requirements. I've made substantial changes to this subject trying to incorporate the best understanding of effective pedagogy. Prior to 1999, the course was a fairly typical undergraduate engineering course with lectures, recitation, weekly homework assignments, a small end-of-semester design project, and a few written exams. The current version of 16.100 includes the following:

In Their Words

The following are some of the Aerodynamics (16.100) students' responses to the questions "What were the best parts of the course?" and "How could the course be improved?" asked in end-of-semester (anonymous) evaluations.

On the pre-class homework:

- ○ I was initially opposed to the idea that I had to do reading & homework before we ever covered the subjects. Once I transitioned I realized that it made learning so much easier!!
- ○ I was skeptical at first of new techniques like [concept questions], homework on material that hasn't been learned in lecture. In the end, it worked out very well. This has been a course where I really felt like I got my money's worth.
- ○ Prof. Darmofal forces you to learn the subject material by assigning homework that he has not covered in lecture, therefore I have to force myself to read the text and go to office hours. When he does go over in lecture after the Pset is due, I did absorb the material much better.
- ○ Doing homework before the lectures is good … makes actual learning in lectures possible.

On the team project:

- ○ I think the team projects are really good. There are some kinks which need to be worked out and possibly explained sooner, but they really bring us to an understanding of what elements are necessary to incorporate theory into design.
- ○ My group floundered for a while with the project. In the end we got everything to come together, but it was tough to get through. I'm not sure that I would have wanted it any other way, now that I look back on it. I learn best when I struggle with material for a while, provided I have enough time to finally understand it. I had just enough time for the project.
- ○ Although the project was extremely time consuming, it was fun to be able to apply what we were learning to a real aero problem.

On the oral exams:

- ○ The oral exam was a different learning assessment approach that I liked a lot.
- ○ I really like oral exams that stress conceptual knowledge.
- ○ The oral exams are an excellent measure of understanding.
- ○ Oral exams [are the best part of the subject], I think these gave a good opportunity to show what you understand.
- ○ I really like the idea of the oral final. Even though it is scary, it really shows how much you know about the subject, better than any exam would.

- **Concept-based lectures with real-time feedback.** Educational research has shown that for students to develop a strong conceptual framework, misconceptions that have occurred in previous learning must be addressed such that students become dissatisfied with their understanding. To facilitate this, I follow an approach, developed by Professor Eric Mazur at Harvard University, called "peer instruction." In this approach, two or three multiple-choice concept questions are given in a typical one-hour lecture. These questions are designed to include the important concepts of the subject and their common misconceptions. After a couple of minutes of independent reflection, students use handheld remotes to select an answer. A computer charts responses and they are projected, real-time, on a screen for all to see. Depending on the responses, students are given time to interact with each other to discuss their answers and/or a short lecture on the concept is given. The educational research shows that this type of active learning not only can improve student understanding, but also can increase confidence, enjoyment of a subject, and interpersonal skills. Within our department, the peer instruction approach was first used extensively in Unified Engineering (see Steve Hall's article in the 2003-2004 issue of *Aero-Astro*).

- **Weekly (graded) homework on material given prior to being discussed in class.** To increase the effectiveness of the concept-based lecturing, students need to engage the material prior to class. Without this prior engagement, students may not have sufficient background in the material to even understand the conceptual questions being asked. Traditionally, engineering courses almost exclusively assign homework after the concepts have been presented in class. However, to improve student preparation, I give homework assignments (with appropriate reading) on material prior to in-class discussion. With this preparation, the classroom becomes an interactive environment where students are ready to discuss the conceptual difficulties they have faced, and have begun to develop a common language to have this discussion.

- **A semester-long, team-based analysis and design of an aircraft.** Typically, aerodynamics and other advanced engineering topics are taught with a significant focus on theory, but little opportunity to apply theory, especially to problems that approach the complexity faced in the design of modern aircraft. As a result, students perceive they are learning material "just-in-case" they may need it later in their careers. In the project-based approach used in 16.100, the knowledge is immediately applied. Furthermore, the use of a semester-long project provides a context for learning the technical fundamentals as proposed in Aero-Astro's Conceive-Design-Implement-Operate (CDIO) initiative. Over the past four years, two design projects have been developed: one based on a military fighter aircraft, and another on a blended-wing body commercial transport aircraft.

- **Oral examinations.** In addition to changing the in-class pedagogy, I've also modified the exams from a written to an oral format. While written exams can only analyze the information that appears on paper (i.e., the final output of a student's thought process), an oral exam is an active assessment that can provide great insight into how students understand and relate concepts. Furthermore, practicing engineers are faced daily with the real-time need to apply rational arguments based on fundamental concepts. By using oral exams, a student's ability to construct sound conceptual arguments can be readily assessed.

WHAT STUDENTS SAY

During this evolution of 16.100, student evaluation data from end-of-semester surveys has been used to assess the effectiveness of the pedagogy and improve its implementation. The evaluations consisted of quantitative ratings of the effectiveness of the course pedagogy, as well as open-response questions. Here's a synopsis of what the students have said:

	Homework & Textbook	**Lecture**	**Project**
Post 2000	2.78	2.76	2.53
2000	2.48	2.14	2.61

Average student ratings of the effectiveness of different aspects of the course pedagogy for 2000 and post-2000 (2001-2003) semesters. 1 = not effective, 2 = effective, and 3 = very effective

- **The new pedagogy, in its final form, is consistently rated as highly effective.** As shown in the above table, since Fall 2000, the mean student ratings of the effectiveness of the pedagogy are all between effective to very effective.

- **Challenging pre-class homework increases the effectiveness of lecture.** In the Fall 2000 semester, while the pedagogy was as described above, the pre-class homework was designed to encourage reading, but did not require significant engagement of the material. Student feedback from the Fall 2000 course evaluations led to a decision to increase the difficulty of the homework. The post-2000 data shows a statistically significant increase in the mean effectiveness of not only the homework but also the lectures.

- **A learning transition occurs over the length of the semester.** The open-response questions show that students are often initially hesitant about pre-class homework, but by the end of the semester they recognize the benefits of this technique. Students' comments (see "In Their Words," page 26) also reinforce the link between the pre-class homework and the effectiveness of the lectures.

- **The effective implementation of the team project is difficult.** One of the most challenging aspects of the new pedagogy has been the implementation of the team project. The project has multiple facets (in particular, the wind tunnel experiments and the computational simulations) that must be successfully managed. Furthermore, keeping 10 or more teams of four students functioning effectively can be highly time-consuming for both the faculty and the students. As Aero-Astro continues to incorporate CDIO throughout the undergraduate curriculum, the effective use of projects will be a challenging issue to address.

Students (from left) Amy L. Wong, Ching-Yu Hui, James Modisette, and Rachel Lee discuss their project team's aerodynamic analysis of a blended-wing body aircraft with Professor David Darmofal during a weekly work session. (William Litant photograph)

- **Oral exams are an effective assessment strategy.** Many students find the oral exam to be a much more accurate representation of their understanding than more traditional written exams. In fact, several students have said that the oral exams were the best parts of the course.

OUTLOOK

Pedagogical reform will continue as the findings of educational research impact engineering campuses across the country. In our department, we're already feeling the impact. The voices of our students show that these new pedagogies, while challenging to implement, can lead to a more effective learning environment.

David L. Darmofal is a MacVicar Fellow and an associate professor in the MIT Department of Aeronautics and Astronautics. He teaches Aerodynamics (16.100) and Computational Methods for Aerospace Engineering (16.901). Darmofal's research interests include computational fluid dynamics, robust design of jet engines, and engineering education. He may be reached at darmofal@mit.edu.

Without their computerized flight control systems, inherently unstable aircraft, like the Grumman X-29, would be unflyable. (NASA photograph)

CONFIDENCE IN THE CODE

By Nancy G. Leveson

Computers and software are integral to the safe and successful operation of hardware from the microwave on the counter to probes in deep space — and when there's a software error, the results can be disastrous

Computers profoundly impact engineering, both as a tool to assist engineers in their work and as an embedded component (often performing a control function) in engineered systems. Virtually nothing is engineered or manufactured in the United States today without computers affecting the design, manufacturing, and operation. Not only do products incorporate computers to operate better or cheaper ("smart" automobiles and appliances are examples) but complex systems, such as unstable aircraft and many space vehicles, are being designed that can't operate without computers. Hence, the reliability of software has become as critical as ensuring the strength of nut and bolts.

At the same time that computers are becoming indispensable in controlling complex engineered systems, quality, and confidence issues are increasing in importance. We increasingly hear about failures due to computers. Software errors have resulted in loss of life, destruction of property, failure of businesses, and environmental harm. Software has been called "the Achilles' heel of weapon development." Large government projects are in trouble or have been canceled because of difficulty in assuring the quality of the software. The cost and length of many of our complex engineering projects are reaching impractical limits, often due to delays in the software development and assurance activities, and half the development costs of large aerospace systems are now attributable to software. There needs to be some way to reduce costs and schedules so that systems are not technically obsolete before they are completed, and costs so high that their construction and operation cannot be justified.

One reason for the problems is that software-intensive systems require standard engineering techniques to be extended to deal with new levels of complexity, new types of failure modes, and new types of problems arising in the interactions between system components, including human-computer interaction problems. Some examples of system accidents (those arising in component interaction, not simply from individual component failure) are the losses of the Space Shuttle Columbia and the Mars Polar Lander, and the 2003 failure of the Northeast power grid.

Computers exacerbate such interaction problems by allowing levels of complexity and coupling with more integrated, multi-loop control in systems containing large numbers of dynamically-interacting components. We are now attempting to build systems where the interactions between the components cannot be thoroughly planned, understood, anticipated, or guarded against. The problem is intellectual manageability: increased complexity makes it difficult for the designers to consider all the potential system states or for operators to handle all normal and abnormal situations and disturbances safely and effectively. The limits of what we can build are changing from structural integrity and the physical limits of materials to the intellectual limits of those designing, operating, interacting with, and maintaining our engineered systems.

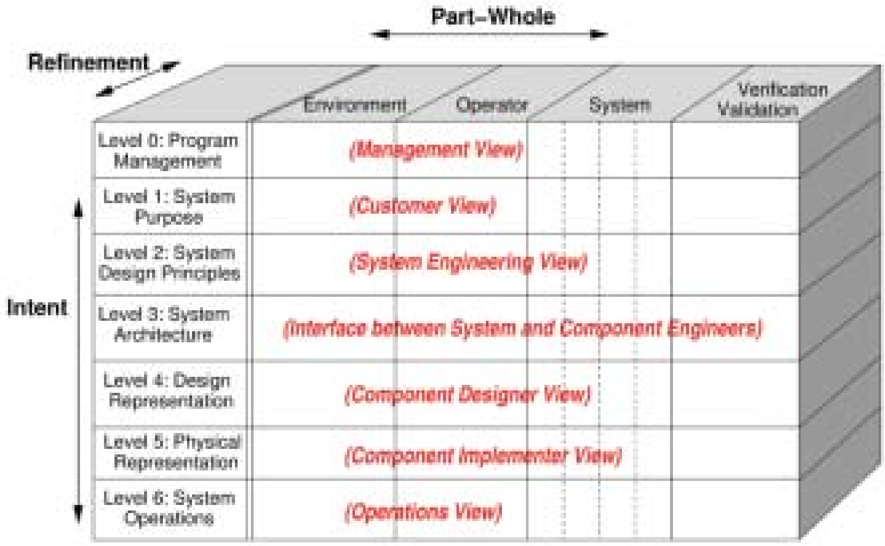
My students and I are working on ways to stretch the limits of complexity and intellectual manageability of the systems we can build with reasonable resources and with confidence in their expected behavior, particularly safety and mission accomplishment. While our primary emphasis is on aerospace systems and applications, our research results are applicable to complex systems in such domains as transportation, energy, and medicine. In all of this work, we take a systems approach to engineering that emphasizes enhanced system-level modeling, analysis, and visualization tools as well as integration of the organizational, political, and cultural aspects of system construction and operation with the technical aspects.

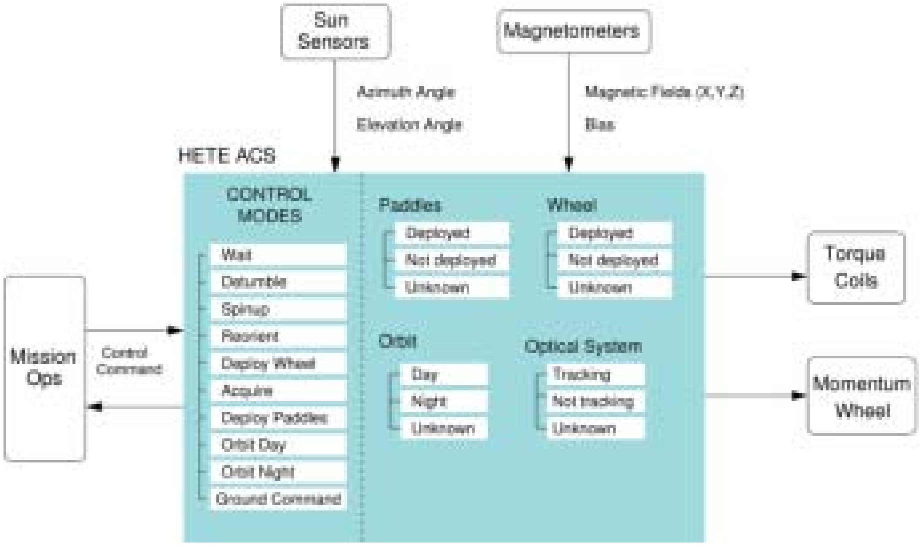
Our current research projects include executable specification languages, interactive visualization of complex system behavior, reusable component-based system architectures, human-centered system design, and design for safety.

Executable specification languages. Specifications and models provide a means for understanding complex phenomena, and recording that understanding in a way that can be communicated to others. As complexity grows, the use of prototyping to evaluate designs becomes increasingly impractical. The alternative is to use behavioral and structural models of the system design, essentially executable specifications, along with advanced analysis tools and simulation environments, to evaluate the system design before construction begins and find and eliminate errors early in the development process.

Usability is a large component of this research: the executable specification languages must be readable and usable with minimal training by a large variety of domain experts if model-based system engineering is to become a practical reality. At the same time, to allow for automated analysis tools, the languages must have a formal (mathematical) model as their foundation. The figure to the right shows a new structuring mechanism, called Intent Specifications, based on research in cognitive psychology and how to support expert problem solvers and stretch their intellectual limits. Most specifications use refinement and decomposition to deal with complexity, but intent specifications add a third type of abstraction called intent abstraction. This new type of abstraction allows capturing design rationale in the structure of the specification and providing complete traceability from high-level requirements to design decisions to implementation through the use of

Intent Specifications are a new way of structuring specifications using seven models or views of the system. Hyperlinks within and between models provide information about why a particular design decision was made and traceability between levels of specification. Level 3 includes formal, executable models of the behavioral system requirements, including required operator behavior.





The graphical part of a Level 3 model of the HETE (High-Energy Transient Explorer) spacecraft attitude control system. As the model executes, the inputs, outputs, and current state-of-the-state variables light up on the screen.

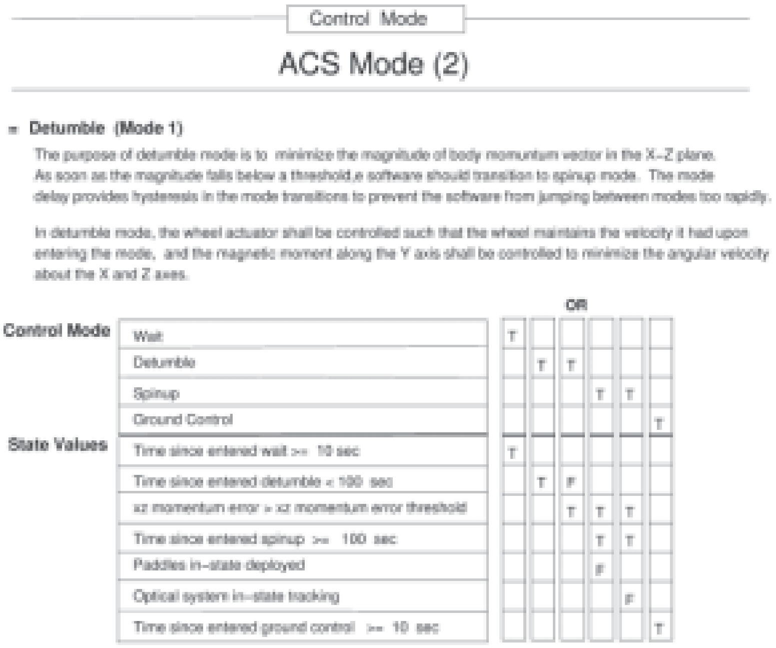
hyperlinks within and between intent specification levels.

The third level of an intent specification contains a formal, executable model of the black box behavior and interactions among the system components (including human procedures). Because the models are formal, they can be mathematically analyzed for important properties, such as completeness and consistency, and test cases and code can be automatically generated from them. These ideas have been transferred to industry through a company some former students and I started 10 years ago, Safeware Engineering Corporation, to provide engineering services and tools to the aerospace, defense, automotive, and medical industries and to act as a conduit for rapidly infusing our research results in industry applications as soon as they are proven in our laboratory.

Interactive visualization. Even well-structured specifications for very complex systems can overwhelm human intellectual capabilities. The use of multiple views and interactive visualizations of system design can enhance the intellectual manageability of complex system engineering tasks and assist people in understanding complex system designs. Research on interactive visualization should not only be useful in system design, but also in training and operations, where the complexity of the automation we are designing is confusing operators and those performing sustainment activities. Interactive visualization could be used as a tool both for training operators and for providing real-time information about the operation of the automation to assist with operational decision-making and monitoring activities. Although engineers use ad hoc visualizations, there exists no theory for developing effective ones. Our goal is to provide a theoretical foundation for designing interactive visualizations of complex system design and behavior for use by system designers, operators, and maintainers.

Reusable component-based system architectures. Using these specification and visualization tools, it is possible to build domain-specific, reusable component-based system architectures. We have demonstrated how to create a generic spacecraft architecture in which reusable specifications and models can be easily and quickly tailored for a specific spacecraft design, executed and validated using simulation and formal analysis, and then either manually or automatically transformed into software or hardware. Such reuse, however, is dependent on the ability to record design rationale and underlying assumptions so that the changes necessary for particular applications of the architectural components can be determined. Again, this goal can be accomplished using Intent Specifications. We are currently designing a prototype software product-line architecture for the new space exploration initiative.

Human-centered system design. Complex systems, now and for the foreseeable future will be composed of teams of humans and computers working together to achieve system goals. Humans have not been eliminated from most high-tech systems, but their role has changed significantly — often they are monitors or high-level managers of the automation, which directly (autonomously) controls the system. At the same time, the complexity of the automation design is contributing to new types of human errors, a factor in most of the A320 accidents and the crash of a Boeing 757 near Cali, Columbia. To prevent these types of errors, I am working on ways to design automation to eliminate or reduce computer-related human errors such as mode confusion, to optimize the allocation of tasks among humans and automation, to enhance learnability, and to improve the training of humans to interact with automation.



An example of the specification of the logic in the Level 3 models. The spacecraft will enter Detumble Mode if any of the columns in the logic table evaluate to true. Although easy to read, this table can be executed by a computer and used in the simulations. Writing low-level code is not necessary to prototype the software. Completeness, consistency, and various types of hazard analysis can be performed automatically on the logic specifications.

ACS Mode (2)

- **Detumble (Mode 1)**

The purpose of detumble mode is to minimize the magnitude of body momentum vector in the X-Z plane. As soon as the magnitude falls below a threshold,e software should transition to spinup mode. The mode delay provides hysteresis in the mode transitions to prevent the software from jumping between modes too rapidly.

In detumble mode, the wheel actuator shall be controlled such that the wheel maintains the velocity it had upon entering the mode, and the magnetic moment along the Y axis shall be controlled to minimize the angular velocity about the X and Z axes.

		OR					
Control Mode	Wait	T					
	Detumble		T	T			
	Spinup				T	T	
	Ground Control						T
State Values	Time since entered wait >= 10 sec	T					
	Time since entered detumble < 100 sec		T	F			
	xz momentum error > xz momentum error threshold			T	T	T	
	Time since entered spinup >= 100 sec				T	T	
	Paddles in-state deployed				F		
	Optical system in-state tracking					F	
	Time since entered ground control >= 10 sec						T

Some space mission failures or losses resulting from software errors

ARIANE 501

On the Ariane 5's June 1996 maiden flight, the European commercial launch vehicle veered off its flight path, broke up, and exploded. Investigators reported that the primary cause of the failure was complete loss of guidance and attitude information due to specification and design errors in inertial reference system software.

SOLAR HELIOSPHERIC OBSERVATORY

Contact with the Solar Heliospheric Observatory spacecraft, a NASA–European Space Agency effort to perform helioseismology and monitor the solar atmosphere, corona, and wind, was lost in June 1998. The loss was preceded by a routine calibration of the spacecraft's roll gyroscopes and a momentum management maneuver. The flight operations team had modified the ground operations procedures to reduce operations costs and streamline operations, minimize science downtime, and conserve gyro life. Errors in making the software changes, in performing the calibration and momentum management maneuver, and in recovering from an emergency safing mode led to the loss of telemetry. Re-establishing communication with the spacecraft took four months.

TITAN/CENTAUR/MILSTAR

A Titan IV B-32/Centaur TC-14/Milstar-3 was launched in April 1999 to place a Milstar military communications satellite in geosynchronous orbit. An incorrect roll rate filter constant zeroed the roll rate data, resulting in the loss of roll axis control and then yaw and pitch control. The loss of attitude control caused excessive firings of the reaction control system and subsequent hydrazine fuel depletion. This erratic vehicle flight led to an orbit much lower than desired, placing the satellite in an unusable low elliptical final orbit instead of the intended geosynchronous orbit. The accident investigation board concluded that failure was due to inadequate software development, testing, and quality assurance for the Centaur upper stage.

MARS CLIMATE ORBITER

In September 1999, the Mars Climate Orbiter was lost when it entered the Martian atmosphere in a lower than expected trajectory. The root cause of the accident was a mix-up when outside engineers provided navigational software based on English measurements while NASA assumed they had used metric units.

MARS POLAR LANDER

The most likely scenario for the December 1999 loss of the Mars Polar Lander is that a problem occurred during landing leg deployment from stowed condition to the landing position. The descent engines were to be shut down by a flight software command when touchdown was detected. However, the touchdown sensors characteristically generate a false momentary signal at leg deployment. While this false signal was understood to occur, the software requirements did not specifically describe this event and the designers did not account for it. It is believed that 40 meters above the Martian surface the software interpreted the spurious signals generated at leg deployment as touchdown, shutting down the engines and allowing the lander to plummet to its destruction.

It's believed that the 1999 loss of the Mars Polar Lander was the result of software shutting down the landing engines while the craft was still 40 meters above the Martian surface. (NASA illustration)

Design for safety. At the foundation of the current limitations in engineering for safety and mission assurance is the almost exclusive use of a model of accident causation that assumes such accidents arise from a chain of failure events and human errors. While satisfactory for the relatively simple electromechanical and industrial systems for which the model was developed, it does not explain system accidents, and it is inadequate for today's complex, software-intensive, human-machine systems. After much frustration in trying to adapt the old model to the new engineering environment, I created a new accident causation model based on systems and control theory rather than reliability theory that can serve as the foundation for new and improved approaches to accident investigation and analysis, hazard analysis and accident (loss) prevention, risk assessment and risk management, and performance monitoring. The model integrates organizational and management factors (the safety culture) with the technical aspects of accident causation in order to fully understand the origin of accidents and successfully prevent them. Our new hazard analysis methods based on this model are now starting to be applied to defense and aerospace system design.

Nancy G. Leveson is a professor in the MIT Department of Aeronautics and Astronautics, and in the Engineering Systems Division. She is a member of the National Academy of Engineering, and has received awards for her research including the AIAA Information Systems Award, the ACM Allen Newell Award, and the ACM Outstanding Software Research Award. Her research activities have focused on system safety engineering, software engineering, human-computer interaction, and system engineering for software-intensive systems. She may be reached at leveson@mit.edu.

Moe Win's ultrawide bandwidth research is exploring intriguing possibilities for wireless systems and networks that operate in difficult situations. Among other advantages, UWB transmission provides anti-jam and low probability of detection capabilities. (William Litant photograph)

Multipath wireless at the threshold of
ROBUST, LOW-COST COMMUNICATION

By Moe Win

The demand for high quality, fast, and reliable wireless access grows daily. Current needs, especially within industrial, scientific, and military sectors, suggest that ever-wider bandwidth in various frequency bands will be made available. This has prompted exploration of using larger bands of spectrum, often in challenging environments and over portions of bandwidth that are already in use.

The burgeoning need for wireless access poses significant challenges for networking, communications design, and hardware development. In a wireless setting, the transmitted signal typically arrives at the receiver via many different propagation paths, each of which comes with a different amplitude, delay, and phase shift. Depending on the environment and the particulars of the communication scheme, the number of paths arriving at the receiver can be very large. These paths constructively and destructively add at the receiver. This process, known as multipath fading, varies with time and movement in the environment, and is inevitable in harsh operating areas like cities with dense buildings and narrow streets.

Advanced techniques can turn this disadvantage into an advantage by exploiting the multipath phenomenon to provide robust, low-cost communication. Ultrawide bandwidth (UWB) transmission systems potentially provide such reliable transmission by virtue of their robustness to fading and their superior obstacle penetration. UWB systems use narrow or short duration pulses that result in very large transmission bandwidths, or wideband. The use of this extremely wide bandwidth results in desirable capabilities that are well suited for robust location-aware wireless networks, such as accurate position location and ranging; lack of significant multipath fading because of fine delay resolution; multiple access communications;

and better obstacle penetration due to low frequency components. UWB electromagnetic propagation exhibits some intriguing characteristics for wireless systems and networks that must operate in difficult situations. Among other advantages, UWB transmission, combined with spread spectrum techniques, provides anti-jam and low probability of detection and interception capabilities due to low power operation in such a large bandwidth.

In 2002, a landmark ruling by the FCC authorized the unlicensed use of UWB technology. This brought greater attention to the area and opened the way for further research into UWB, whose applications range from high-speed wireless access to emergency services, unmanned aerial vehicle communications, and homeland security systems. My research group at MIT's Laboratory for Information and Decision Systems, along with an interdisciplinary team from the Institute's Aeronautics and Astronautics Department, Microsystems Technology Laboratories, Computer Science and Artificial Intelligence Laboratory, and Electrical Engineering and Computer Science Department, is exploring many of these possibilities. Here, we highlight two major projects: robust distributed sensor networks, and a network research testbed, conducted under the auspices of the Charles Stark Draper Laboratory and the National Science Foundation, respectively.

AMONG OTHER ADVANTAGES, UWB TRANSMISSION, COMBINED WITH SPREAD SPECTRUM TECHNIQUES, PROVIDES ANTI-JAM AND LOW PROBABILITY OF DETECTION AND INTERCEPTION CAPABILITIES

ROBUST DISTRIBUTED SENSOR NETWORKS

We are currently developing advanced communication technologies that enable ad-hoc sensor networks to operate effectively in hostile environments, such as through urban canyons (narrow streets), inside buildings or caves, and under tree canopies, where the conventional methods for location determination and communication are difficult and may fail. Such environments often occur in battlefield conditions that present unique obstacles to reliable communication. Our approach involves a combination of robust physical layer communication technology, robust distributed ad-hoc networking techniques, and navigation and mapping capabilities that take advantage of the inertial measurements and UWB's fine-time resolution capabilities.

UWB communications can be achieved by a variety of modulation techniques. Our interest is in developing simple and reliable UWB transmission schemes that exploit the multipath diversity inherent in the propagation environment. In particular, we are investigating transmitted-reference signalling schemes, which involve the transmission of a pair of data and reference signals that can be separated at the receiver. In this case, the demodulation process can be as simple as performing correlation between the data and reference signals. Since the reference does not need to be locally generated at the receiver, the long acquisition times associated with conventional UWB receivers can be greatly reduced. This signalling scheme is especially attractive in wireless sensor network applications, involving a large number of low-cost sensor nodes with severe power constraints and limited signal processing capabilities.

Distributed sensor networks require a dependable ad-hoc networking capability for communication between a large number of nodes in a hostile operating environment. Nodes in the ad-hoc network can be moving, and connectivity among them can change rapidly. The future combat environment is likely to include both mobile and stationary nodes. A key goal of this project is thus to develop reliable network architectures and routing algorithms, combined with robust UWB transmission techniques, that can function effectively with a mix of rapidly moving aircraft, slower ground vehicles, and stationary elements.

Moe Win performs a UWB experiment under a Fulbright Fellowship during a recent collaborative visit to the Centre for Wireless Communication in Oulu, Finland. Win used a sophisticated wideband spectrum analyzer to measure the aggregate interference of a number of UWB transmitters (interferers). He placed transmitters in a semicircle equidistant from the receiving antenna. Spectrum measurements were then made when a varying number of transmitters were active at various distances.

NETWORK RESEARCH TESTBED

In this project we are developing a UWB network testbed that jointly considers networking, communications design, and hardware implementation. The goal is creation of a high-performance wireless link through sophisticated signal processing, while minimizing the overall energy use. To facilitate ubiquitous wireless access, tomorrow's networks must be scalable and compatible with existing systems sharing the same spectrum. To this end, we are investigating the aggregate interference from spatially distributed UWB emitters.

By monitoring the entire spectrum, the frequency plan and transmission schedule can be dynamically adjusted for optimizing bandwidth and energy efficiency. Processing a smaller portion of the spectrum greatly simplifies the radio transceiver architecture. This enables a partitioning of a UWB receiver into a set of identical modules that are relatively simple to design and build. Furthermore, with technology scaling, the multi-channel architecture will integrate multiple transceivers on the same chip, allowing scalability in bandwidth with power dissipation.

UWB TECHNOLOGIES COULD PROVE IDEAL FOR UNMANNED & AERIAL VEHICLES AS THEY FLY THROUGH CANYONS AND BETWEEN CITY BUILDINGS

The novelty of the proposed UWB network testbed is twofold. First, the testbed will contribute to the development of nascent UWB technology at the device level, and is the first attempt at integrating UWB into a network. Second, in contrast to previous network designs, which prevent direct exchange of information between various layers, we will adopt a flexible design that enables cross-layer optimization. Such a design is particularly beneficial in wireless environments with scarce resources and severe power constraints. This testbed extends our capabilities well beyond current limits and enables the development of sound, systematic methodologies for the design of wireless access systems.

THE OUTLOOK

UWB technology has a broad range of applications. In future research we plan to investigate some of these exciting possibilities, including advanced localization systems, robust wireless networks, and air-to-ground communications. Coordinated unmanned aerial vehicles, for example, are expected to operate in dense multipath and rich scattering environments, such as through canyons or between city buildings. UWB techniques are ideal solutions for such harsh channels.

The field of wideband wireless communications is rapidly expanding, necessitating international collaboration. Over the last five years, we have established active international research collaborations with researchers at the University of Bologna in Italy, University of Lund in Sweden, Swiss Federal Institute of Technology in Switzerland, and University of Oulu in Finland. An important part of this international collaboration has been a broad exposure to different teaching and work cultures. We look forward to continuing these productive research and teaching partnerships.

Moe Win is an associate professor in the Aeronautics and Astronautics Department and the Laboratory for Information and Decision Systems. His main research interests are the application of mathematical and statistical theories to communication, detection, and estimation problems. In 2004, he received a Fulbright Fellowship and the Presidential Early Career Award for Scientists and Engineers from the White House. He is an elected Fellow of the IEEE, cited "for contributions to wideband wireless transmission." Win may be reached at moewin@mit.edu.

Artist's impression of the Mars Gravity Biosatellite in low earth orbit. The spacecraft will spin to create artificial gravity, exposing the 15 mice passengers to a simulated Martian environment before returning them to earth. (Georgi Petrov illustration)

OF MICE AND MARS

By Paul Wooster and Erika Wagner

This is what interdisciplinary learning is all about: a project blending hardware design with biomedical engineering, systems engineering, biology, and management. Just over three years ago, a small group of MIT students laid the groundwork for a new international spacecraft development program. Having engaged well over 150 graduate and undergraduate students from across the Institute to date, the Mars Gravity Biosatellite Program is offering students the unparalleled opportunity to design, manage, build, test, and launch their very own world-class research spacecraft and help hasten the day when human explorers set foot on Mars.

In the microgravity environment aboard Space Shuttle and Space Station, astronauts suffer from severe medical deconditioning, losing bone density, muscle strength, and cardiovascular fitness, as well as experiencing significant changes in balance and coordination. While it seems likely that the partial gravity on Mars, about one-third of that on Earth, will help lessen some of these challenges, the actual magnitude of the problem on the Martian surface remains a mystery.

Here at MIT, student members of the Mars Gravity Biosatellite Program have offered an approach to answer this challenge. Initiated in August 2001, this student-driven, international satellite design collaboration unites students from MIT, the University of Washington, and the University of Queensland to develop an uncrewed orbital research platform for studying the effects of reduced gravity on mammalian physiology. The students at MIT represent a mix of undergraduate and graduate students from across the entire Institute, including a large contingent from Aero-Astro, unified by the conviction that they are making a major contribution toward the human exploration of space.

Their biosatellite, with its payload of 15 mice will catch a ride from Cape Canaveral to low earth orbit aboard the Falcon I launch vehicle, currently under development by the Space X company and slated for its first launch in early 2006. Once on orbit, the spacecraft will spin up to create an artificial gravity environment equivalent to the surface gravity of Mars. At the end of the five-week mission, the spacecraft bus will be jettisoned, and the reentry vehicle will begin its descent to the Woomera Prohibited Area of the Australian outback, descending under parachutes and cushioned by airbags to ensure a safe recovery of the mice. In-flight and post-flight observations will chart the first in-depth data point for mammalian physiology between microgravity and Earth's 1-g, a vital step towards preparing for human exploration of space.

The Mars Gravity Biosatellite will be one of the most complex spacecraft built by a university-based team, providing extensive data telemetry, atmospheric re-entry capability, and a record-breaking autonomous life support system. To date, the program has engaged more than 300 students across the three partner universities. MIT spearheads the program management efforts, development of the science package, systems engineering, and design of the Payload Module, providing life support capabilities and data telemetry/storage from on-board experiments. Partners at the University of Washington lead design of the Spacecraft Bus, including structures, propulsion, and power systems, and the University of Queensland Centre for Hypersonics Entry Descent and Landing system carries the payload safely back to Earth at the conclusion of the mission with heat shield, parachutes, and airbags. These complex systems offer students a one-of-a-kind training experience to complement classroom exposure with value hands-on design, management, and product development.

Where once sat a dozen students working on a conceptual design for a university competition now stands a full-fledged flight program. Students are working closely with industry partners, faculty and alumni mentors, and a worldwide network of advisors to take their concepts from paper to flight hardware. Partnerships with experienced engineers at the MIT Center for Space Research, Payload Systems Inc., Aerojet Corp., and Draper Laboratory have enabled students and recent grads to maintain project leadership roles while substantially reducing mission risk. Their meager budget for building rough prototypes and traveling to present their work has matured into a $30 million funding goal, a bargain by spacecraft standards, but manageable thanks to the dedicated efforts of this mostly volunteer army. Generous alumni donations have played a tremendous role in funding efforts to date, enabling departmental support to help the students bring to life this world-class design effort.

But the project is not in orbit just yet. To date, the team has raised nearly a $1 million in cash and in-kind donations from the three partner universities, individual donors, Space Grant, NASA, and related corporations. They have also secured a herculean commitment to cover nearly half the cost of their launch vehicle. The MIT Department of Aeronautics and Astronautics has provided major support towards the effort ranging from significant financial contributions enabled by alumni support, to facilities and equipment usage, to the extensive advice and encouragement from the Department's faculty and staff. Now, with a preliminary design review just around the corner, the team is turning primarily to NASA to enable its dreams to reach orbit. With that organization's recent commitment to exploring "the moon, Mars, and beyond," the group's efforts have become even timelier for NASA. Given appropriate funding from NASA, the mission could leave the ground as early as mid-2008.

Mars Gravity Team members (from left) Anna Massie, Valentina Lugo, Paul Wooster, and Erika Wagner with a prototype animal habit unit and water delivery system. Each mouse will be individually housed in one of these units as they orbit the Earth aboard the Biosat. (William Litant photograph).

The Mars Gravity Biosatellite will deliver broad, groundbreaking data on the physiological challenges of living in reduced gravity, but the students will tell you that the benefits of their work need not stop there. The platform they are designing is intentionally modular, capable of carrying aloft and bringing home a wide variety of experiments that are either incompatible with existing facilities or could simply be accomplished more cheaply on an uncrewed satellite. Altering the vehicle's spin rate would enable investigations in a wide variety of accelerational environments. Extending the orbit would provide exposure to radiation within or outside the van Allen belts. Payloads too hazardous for Space Station, including novel propulsion elements and radiation sources, could be handled with ease. And in the absence of human activity, acceleration levels can be minimized far beyond what is possible on crewed platforms, opening a broad range of opportunities for materials and physical sciences research. Indeed, such a small, low-cost, returnable research platform could provide NASA with a capability that it has been without since the 1960s, freeing other resources to focus on the main agenda of exploration.

For many of the Mars Gravity students, this opportunity comes at the end of a long string of open doors in science and technology. They have been inspired in their time by that special teacher, program, or competition, and they recognize that chances like this are of one the greatest motivators to aspiring young engineers and scientists. To that end, members of the program have developed a number of outreach initiatives, extending the reach of Mars Gravity beyond the campuses of three universities. Speaking to Scout troops and classrooms, running hands-on workshops, and inviting high school interns to join the team during the summer months allow the Mars Gravity teammates to contribute to the communities around them. Just maybe, such outreach will inspire the next generation to embrace the challenges that come their way and to take their own concrete steps towards the stars.

For more information about the program or to learn how you can help, visit the team at http://www.marsgravity.org or email info@marsgravity.org.

Paul Wooster is a research scientist in the Space Systems Laboratory and the Program Manager for the Mars Gravity Biosatellite. He may be reached at pwooster@mit.edu.

Erika Wagner is Ph.D. student in the Harvard-MIT Health Science and Technology program and a research assistant in Aero-Astro's Man-Vehicle Lab. She serves as the Science Director for the Mars Gravity program. She may be reached at elb@mit.edu.

Sheila Windall's official portrait as Secretary of the Air Force. Appointed by President Clinton, she was the first woman to hold this position.

Faculty profile:
A ONE-ON-ONE WITH WIDNALL

By Lauren Clark

MIT engineering professor, chair of the MIT faculty, president of the American Institute of Aeronautics and Astronautics, Secretary of the U.S. Air Force. It's an impressive list of accomplishments for any individual. What's more impressive is that Institute Professor Sheila Widnall was the first woman to secure all of these posts.

Sheila Evans Widnall came to MIT from Tacoma, Washington as one of only 23 women in the class of 1960 — a freshman class of more than 900 students. Encouraged by her undergraduate advisor, Holt Ashley (now an aerospace professor emeritus at Stanford), she went on to earn the S.M. and Sc.D. in aeronautics. She became MIT's first female engineering professor in 1964, and then, the first female chair of MIT's faculty.

Aeronautical engineers around the world are familiar with Widnall's foundational work in fluid dynamics, particularly aircraft turbulence and spiraling air flows.

"She made fundamental contributions to the understanding of aircraft wake decay, which is terribly important for the spacing apart of aircraft during takeoff and landing and which has implications for airport safety and efficiency," says longtime Widnall colleague and former Aero-Astro Head Earll Murman. In 1993, President Clinton appointed Widnall Secretary of the Air Force, making her the first woman to lead a branch of the military. She held that position until 1997. Afterward, she became the first female president of the AIAA.

WHAT WE'RE SEEING IS A VERY PRODUCTIVE COMMUNITY WHERE THERE IS A VERY STRONG ACCEPTANCE OF WOMEN STUDENTS AND FACULTY

More recently, Widnall has focused on the discipline of systems engineering through her role as a board member of the MIT Lean Aerospace Initiative. Her expertise in analyzing complex systems led NASA to tap her as an investigator of the Columbia Space Shuttle accident in 2003. She has given lectures nationwide on that investigation and how it uncovered serious institutional flaws that led to the crash. It's this kind of visibility and experience that makes Widnall an ideal advocate for the Department of Aeronautics and Astronautics' continued leadership in addressing the needs of the aerospace industry.

Partly through Widnall's leadership both on and off campus, the department, MIT, and engineering education as a whole have been transformed. In a recent interview, Widnall discussed her career and how it has intertwined with MIT's evolution over the past half-century. She began by noting MIT's success in attracting women to engineering education.

Q. There are more women in engineering at MIT than ever before. Do you think women engineers here are in the home stretch, or are there still a lot of barriers?

A. I think they're in the home stretch. Beyond MIT, there is nobody, I mean nobody, in this country, except for Smith College, that has engineering departments where women are the majority of the students. Nationally, the percentage of women in engineering schools is about 21 percent. When you tell other schools of engineering that women are the majority of students in at least three of our engineering departments, their mouths hang open. The general sense you have is that [the increase in the number of women] has transformed the Institute. It has had an effect on the women graduate students as well, because what has happened is that these students have transformed the faculty, and then the faculty see the women graduate students in a different light than perhaps 30 or 40 years ago when the numbers were much smaller. What we're seeing is a very productive community where there is a very strong acceptance of women students and faculty.

Q. *Is part of that a change in attitudes regarding women's role in family?*

A. Well, I think that is a challenge. I think the way you have to look at that is that it takes two to have a family. I still remember an incident when I was Secretary of the Air Force: I'm sitting in my flight suit out at Nellis Air Force Base, and I'm talking to the cream of the crop, the top guns, and these guys are saying they want to have more time with their families. I'm blown away. I thought they just wanted bigger guns and more powerful engines.

I would never advise a woman student to lower her sights based on the prediction that balancing work and family will be a difficult problem, because what does that get you? It gets you a kind of second-rate career. You deal with the problems when they come.

Q. *What is the current focus of your work?*

A. What I tell people is that I'm a utility infielder, because I know that whatever free time I might have at any one moment — because of light teaching loads, light committee loads — will be changed dramatically because something will happen, like the [Columbia] Shuttle crash. Being an Institute professor gives me freedom to do things. I had just finished a very intense period of activity chairing the faculty committee on our research policy and openness in classified research and government restrictions. Then the Shuttle crashed, and I went to Houston for nine months. I come back to MIT and start to get my feet wet, and then I'm on the MIT presidential search committee. I'm also on the executive board of the Lean Aerospace Initiative. That's a big project, and I interface with the Air Force and the Department of Defense to make sure that the problems we're working on are the key problems and that we can find a customer for the output of the research.

Q. *What did you learn from the Columbia investigation that you now apply to your work?*

A. I've lectured on the topic of institutional culture and safety issues. I talk about how that sort of failure comes about, and I talk about the responsibility of engineers, a responsibility that goes beyond designing widgets. They have to be responsible for designing organizations as well, and if they find themselves in organizations that are dysfunctional, they have a responsibility to speak out and try to improve the organization, just as they would improve a piece of hardware if they saw a need to do it.

I WOULD NEVER ADVISE A WOMAN STUDENT TO LOWER HER SIGHTS BASED ON THE PREDICTION THAT BALANCING WORK AND FAMILY WILL BE A DIFFICULT PROBLEM, BECAUSE WHAT DOES THAT GET YOU?

Q. *Is that a pretty new idea?*

A. That's an interesting question. Back in the 1920s, engineers had a broader view of their responsibilities.

They were building bridges, and they were building large systems — sanitation systems, for instance — for the public. Then, when we went into World War II, there was this national security response, which demanded a higher level of technical competence. Developing radar, developing computers, engineers, perhaps appropriately, began to get fixated on their ability to design the little bits and pieces of the hardware. So it may be they lost focus on the entire system. We're sort of coming back, and that's what the Engineering Systems Division is all about. I'm a part of that. We're coming back to the point where engineers really have to understand more deeply the entire system, including the societal impact, and then speak out, presenting options for political leaders and society. Maybe the pendulum is swinging back.

Q. What are the Department of Aeronautics and Astronautics' strengths?

A. Our department has been a leader in engineering education. As I travel to other universities, I find that our department is much more interdisciplinary. We're able to work together, we do a lot of team teaching, there's less turf, people are more flexible. So we've been able to introduce important new areas. From my point of view, the frontier of aerospace is the fact that 50 percent of the cost of an airplane is in avionics and information. And so, we remade the department and our curriculum to emphasize that entire package. When I was AIAA president, I tried to do the same for AIAA. I tried to create a new AIAA that would have a significant area in information, systems, computers, communication ... because those are essential parts of aerospace. Because we made these moves, our enrollment has stayed quite strong. What we're offering the students is a modern curriculum, and I think they see that.

Q. Looking ahead, what will the Department's legacy be in 21st century?

A. I think the aerospace industry will remain vital and vibrant, and we are an industry-focused department. So the question really becomes, "What are going to

In 1964, Sheila Widnall became MIT's first woman engineering professor. (MIT Museum photograph) be the most important issues for the aerospace industry?" because one would expect the department to follow along and lead in the underlying technologies. The prediction would be: an increased emphasis on space. This includes both manned and unmanned missions and robotics. That ties in with the information, the sensors, autonomy, computer control, communication, the ability to send something out into space and have it do what you want it to do, remotely. Also, a healthy airline industry — safe and efficient aircraft, air traffic control, more automation with respect to the way we handle flight paths of aircraft and information about what's going on up there. Everything I've said has a strong thrust of information, communication, and control. I'm taking for granted that the structures people will always build strong wings. There will be advances in those disciplines, as well as in engines. But the predominant advances will be in information and in putting it all together, dealing with the complexity of systems. We're dealing with extremely complex systems involving human life, human control, and difficult missions. That becomes a discipline in itself: understanding how to put these various parts of the system together and have it operate safely.

Q. *What is your legacy as an engineer and educator?*

A. As I look back on it, MIT has been extremely important in my life. And I think that partly through my efforts, MIT has been transformed.

A lot of people were working on [the recruitment and retention of women at the Institute], but it is a very different place than when I came in 1956, and I take a certain level of credit for that. I think maybe the same thing can be said of the Air Force. I think I had a big impact on the Air Force. And I guess in both cases, you're talking about great institutions that maybe need just a little, one-degree change in what is basically a good place. All of these institutions require people like me who work hard to make them a better place.

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

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

AEROSPACE COMPUTATIONAL DESIGN LABORATORY

The Aerospace Computational Design Laboratory's mission is to improve the design of aerospace systems through the advancement of computational methods and tools that incorporate multidisciplinary analysis and optimization, probabilistic and robust design techniques, and next-generation computational fluid dynamics. The laboratory studies a broad range of topics that focus on the design of aircraft and aircraft engines. Faculty and staff include David Darmofal, Mark Drela, Bob Haimes, Ali Merchant, David Venditti, and Karen Willcox. Jaime Peraire directs the lab.

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

AEROSPACE CONTROLS LABORATORY

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

COMPLEX SYSTEMS RESEARCH LABORATORY

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

While CSRL's main emphasis is aerospace systems

An MIT Space Systems Lab-Draper Lab concept for a next-generation space capsule designed for NASA's Concept Evaluation and Refinement Study. (See "Space Systems Lab," page 60) and applications, its research results are applicable to complex systems in such domains as transportation, energy, and health. Current research projects include accident modeling and design for safety, model-based system and software engineering, reusable, component-based system architectures, interactive visualization, human-centered system design, system diagnosis and fault tolerance, system sustainment, and organizational factors in engineering and project management.

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

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

GAS TURBINE LABORATORY

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

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

Alan Epstein is the director of the lab. GTL faculty and research staff include David Darmofal, Mark Drela, Fredric Ehrich, Yifang Gong, Edward Greitzer, Gerald Guenette, Stuart Jacobson, Jack Kerrebrock, Ravi Khanna, Carol Livermore, Ali Merchant, Nori Miki, 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, Aero-Astro's newest research laboratory, focuses on the multifaceted interactions of human and computer decision-making in complex socio-technical systems. With the explosion of automated technology, the need for humans as supervisors of complex automatic control systems has replaced the need for humans in direct manual control. A consequence of complex, highly-automated domains in which the human decision-maker is more on-the-loop than in-the-loop is that the level of required cognition has moved from that of well-rehearsed skill execution and rule following to higher, more abstract levels of knowledge synthesis, judgment, and reasoning.

Employing human-centered design principles to human supervisory control problems, and identifying ways in which humans and computers can leverage the strengths of the other to achieve superior decisions together is the central focus of HAL.

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

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

Visit the Humans and Automation Laboratory at http://mit.edu/aeroastro/www/labs/halab/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 management; passenger information and communication; and real-time vehicle diagnostics.

Airline operations are also undergoing major transformations. Airline management, airport security, air transportation economics, fleet scheduling, traffic flow management and airport facilities development, represent areas of great interest to the MIT faculty and are of vital importance to international air transportation. ICAT is a physical and intellectual home for these activities. ICAT, and its predecessors, the Aeronautical Systems Laboratory and Flight Transportation Laboratory, pioneered concepts in air traffic management and flight deck automation and displays that are now in common use. ICAT faculty include Cynthia Barnhart, Peter Belobaba, John-Paul Clarke, Eric Feron, and Amedeo Odoni. R. John Hansman directs ICAT.

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

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

The Laboratory for Information and Decision Systems is an interdepartmental research laboratory that began in 1939 as the Servomechanisms Laboratory, focused on guided missile control, radar, and flight trainer technology. Today, LIDS conducts theoretical studies in communication and control, and is committed to advancing the state of knowledge of technologically important areas such as atmospheric optical communications and multivariable robust control.

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

In addition to a fulltime staff of faculty, support personnel, and graduate assistants, every year several scientists from around the globe visit LIDS to participate in its research program. Currently, 17 faculty members, 20 research staff members, and approximately 110 graduate students are associated with the laboratory. Aero-Astro LIDS faculty are John Deyst, Eric Feron, Daniel Hastings, Eytan Modiano, and Moe Win. The laboratory is directed by Vincent Chan.

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

LEAN AEROSPACE INITIATIVE

The Lean Aerospace Initiative is a continuously evolving learning and research community that brings together key aerospace stakeholders from industry, government, organized labor, and academia. A consortium-guided research program, headquartered in Aero-Astro, and working in close collaboration with the Sloan School of Management, LAI's 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 United States aerospace industry, reinvigorate its workplace, and reinvest in America, using an overarching operational philosophy called "lean."

Now approaching its fifth and most important phase — the transformation, not of discrete units of divisions, but of entire enterprises — LAI's mission is to research, develop, and promulgate practices, tools, and knowledge that enable and accelerate the envisioned transformation of the greater U.S. aerospace enterprise through people and processes. As a consequence, LAI is now in the Enterprise Value Phase, engaged in transforming aerospace entities into total lean enterprises, delivering far more value to all stakeholders than would be possible through conventional approaches.

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 aerospace enterprise, in the process eliminating 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 (director), John Deyst, Wesley Harris, Earll Murman, and Sheila Widnall, and Hugh McManus.

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 Jeffrey Hoffman Dava Newman, and Laurence Young, and the director, Charles Oman. 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/

MATERIALS AND STRUCTURES

The Materials and Structures Group has expanded beyond its historical strengths in aerospace composites, aeroelasticity and active/controlled structures to include activities in the area of computational mechanics and research into microelectromechanical systems. In computational mechanics there are projects on high-performance simulation of blast-structure interaction aimed at the design of civil and military structures of enhanced survivability to terrorist threats, modeling of the effective mechanical response polycrystalline materials informed with microstructural features of deformation and failure, and computational modeling of materials for the MIT's new Institute for Soldier Nanotechnologies. Microelectromechanical systems activities include the development of new materials for inclusion in microelectromechanical systems, the modeling of key processes, such as wafer bonding and performing material characterization at small scales. The results from this research are helping support projects such as the MIT MicroEngine and MicroRocket Projects. Other projects include: structural health monitoring for composites, accelerated insertion of materials (composites), fatigue of hybrid laminates, actively conformable aerodynamic control surfaces, highly flexible active composite wings, and the piezo-induced fracture of adhesive joints. Faculty include Paul Lagace, Raul Radovitzky, and Brian Wardle.

THE PARTNERSHIP FOR AiR TRANSPORTATION NOISE AND EMISSIONS REDUCTION

The Partnership for AiR Transportation Noise and Emissions Reduction, which was launched in 2004, is an MIT-led FAA/NASA/Transport Canada-sponsored Center of Excellence. PARTNER's goal is to be a world-class research organization closely aligned with national and international needs, and which leverages a broad range of stakeholder capabilities, thereby fostering breakthrough technological, operational, policy and workforce advances for the betterment of mobility, economy, national security and the environment. PARTNER represents the combined talents of nine universities, three federal agencies, and 29 organizations spanning a range of interests from local government to industry. Industry participants include General Electric, Pratt & Whitney, Rolls-Royce, Boeing, Bell Helicopter, Cessna, Delta Airlines, UPS, Gulfstream, Lockheed-Martin, Sikorsky, the Air Transport Association and other smaller organizations.

During its first 18 months, PARTNER conducted continuous descent approach flight tests with more than 100 UPS aircraft at the Louisville International Airport, made particulate matter measurements on hundreds of aircraft at another major U.S. airport, conducted a field study of low frequency noise at Dulles International Airport, and led the drafting of *"Report to the U.S. Congress, Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions."* PARTNER has many other current projects and its research portfolio is growing.

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

Visit The Partnership for AiR Transportation Noise and Emissions Reduction at http://web.mit.edu/aeroastro/www/partner/or http://mit.edu/aeroastro/www/people/waitz/ for related research activities

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 the electrical, rather than chemical energy propels spacecraft. The benefits are numerous and important, that is the reason why many communication satellites and scientific missions are turning to electric propulsion systems. In the future, these plasma engines will allow people to do such things as explore in more detail the structure of the universe, increase the lifetime of commercial payloads or look for signs of life in far away places. Other areas of research include microfabrication, numerical simulation, arcjet thrusters, numerical simulation, Hall thrusters, space tethers, orbit optimization and spacecraft-thruster interaction. Manuel Martinez-Sanchez directs the SPL research group.

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

The Gerhard Neumann Hangar, added to the rear of Building 33 as part of the MIT Department of Aeronautics and Astronautics Learning Laboratory, offers space for students to construct and test large projects. See article, page 15. (Nick Wheeler photograph, Cambridge Seven Assoc.)