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AERO-ASTRO

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DESIGN

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Photographs by William T.G. Litant, except as noted.

Cover: Julia Throuer ('05) takes preflight measurements on a calibration model in the MIT Wright Brothers Wind Tunnel. Aero-Astro students are exposed to substantial amounts of hands-on engineering as part of the department's conceive-design-implement-operate (CDIO) educational strategy.

The mission of the Massachusetts Institute of Technology Aeronautics and Astronautics Department is to prepare engineers for success and leadership in the conception, design, implementation, and operation of aerospace and related engineering systems. We achieve this through our commitment to educational excellence, and to the creation, development, and application of the technologies critical to aerospace vehicle and information engineering, and to the architecture and engineering of complex high-performance systems.

The MIT Aeronautics and Astronautics Department is home to some of the world's leading aerospace faculty members, students and staff. Our community includes a former space shuttle astronaut, a former secretary of the Air Force, two former NASA associate administrators, three former Air Force chief scientists, 10-13 members of the National Academy of Engineering and 12-14 fellows of the American Institute of Aeronautics and Astronautics.

Our research and teaching range from silent aircraft, to shirt button-size gas turbine engines; to highly flexible space suits woven skin-tight on their inhabitants; to unmanned helicopters capable of complex maneuvers without human intervention; to constellations of tiny satellites that in concert far outperform the single, large satellites of the past; to the development of ultra-wide bandwidth communications. These projects will make our environment cleaner and quieter; improve our health and safety; increase our mobility; heighten our efficiency; enable us to explore frontiers far beyond our current limitations.

We're immensely proud of our past, but our focus is on the future. The department is implementing a strategic plan to reaffirm our role in the intellectually and industrially robust field of aerospace. The new vision of the department that emerges stands on three broad disciplinary bases: the traditional engine and airframe disciplines; the disciplines of real-time system-critical aerospace information engineering; and the disciplines required to architect and engineer extremely complex systems. We have also reformed our educational content and pedagogy through our conceive—design—implement—operate (CDIO) initiative, which is capturing the interest of universities throughout the world.

To chronicle and celebrate Aero-Astro's recent innovations in technology and engineering education, we have published this review, *Aero-Astro*, highlighting just a few of our research and educational activities. Within these pages we also profile two of the people—an alumnus and a professor— who are making Aero-Astro's mark on the world.

The subjects of the articles in *Aero-Astro* represent but a microcosm of our research and our superbly talented people. We'd like to tell you much more. We encourage you to learn more about our research by visiting http://www.mit.aero and about the CDIO Initiative at http://www.cdio.org. You're welcome to contact us for more information, or better yet, let us know when you can visit the department in Cambridge and we'll arrange a tour for you.

Wesley Harris

Ian Waitz

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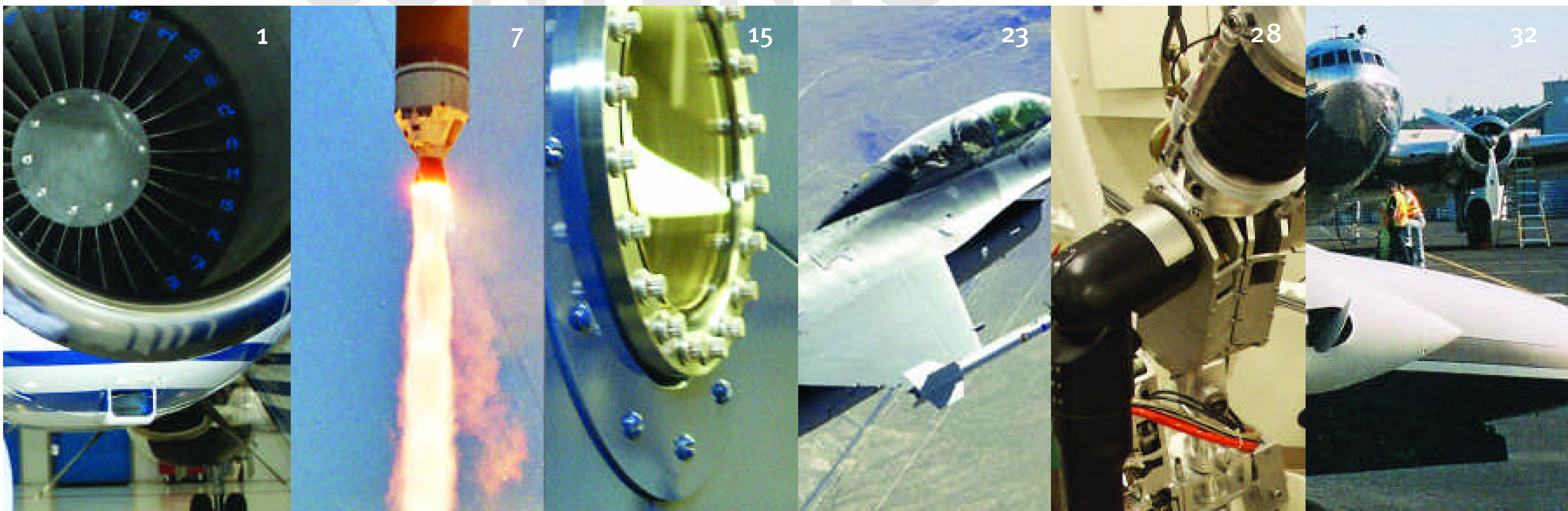


Professor John-Paul Clarke's Continuous Descent Approach procedure for reducing the noise of landing aircraft is attracting aviation authority's attention around the world.

an innovation in
AIRCRAFT NOISE REDUCTION

by John-Paul Clarke

Most attempts to reduce the noise impact of landing aircraft are expensive—modifying aircraft, soundproofing buildings, buying and demolishing homes. But now, an innovative MIT-developed landing procedure is reducing the noise of landing planes, cutting aircraft operating costs, and generating a great deal of interest at airports around the world.

It's no surprise: community concerns about aircraft noise are constraining the growth of aviation. Because of the increasingly active and aggressive legal opposition to airport expansion by residents in impacted communities, many runway expansion projects have been delayed or abandoned. The net effect is fewer that less than five additional runways have been built at the 30 busiest US airports within the last 10 years resulting in greater delays and congestion. Since airports are the nodes of the air transportation system, capacity limitations at the busiest nodes limit the capacity of the entire system.

A number of measures have been adopted to address the issue of aircraft noise. These measures include: phasing out noisier aircraft and introducing aircraft with quieter engine technology; enforcing nighttime curfews on the operation of some or all aircraft; and insulating (or purchasing and demolishing) homes that are severely impacted by aircraft noise. While these measures have reduced the impact of aircraft noise, they have not lessened the opposition to airport expansion. Given the relatively wide implementation of the measures described above, and the potential capacity crisis in the national and international airspace system, there is a critical need for new solutions.

One promising approach to reducing the impact of noise in communities near airports is to change the way aircraft are operated when they are in the vicinity of airports. Late in 2002, I had the privilege of leading a team of researchers in conducting a first-of-its-kind flight experiment at Louisville International Airport to validate our ideas for noise reduction. With my research colleagues from Boeing Commercial Airplane Group, Boeing Air Traffic Management, NASA Ames Research Center and NASA Langley Research Center, I worked with the Regional Airport Authority of Louisville and Jefferson County, the Federal Aviation Administration and United Parcel Service to design and flight test a continuous descent approach (CDA) procedure for the specific airport and airspace constraints at Louisville. The goals of the experiment were (a) to determine whether current aircraft were capable of performing continuous decent approach procedures as designed, (b) to examine the piloting and aircraft performance issues associated with these procedures, and (c) to demonstrate the significant noise benefits that could be achieved with the implementation of advanced noise abatement approach procedures.

United Parcel Service found that its 767s participating in the MIT noise-reduction experiment not only made quieter descents; they also saved about 500 gallons of fuel. (Photo courtesy UPS)

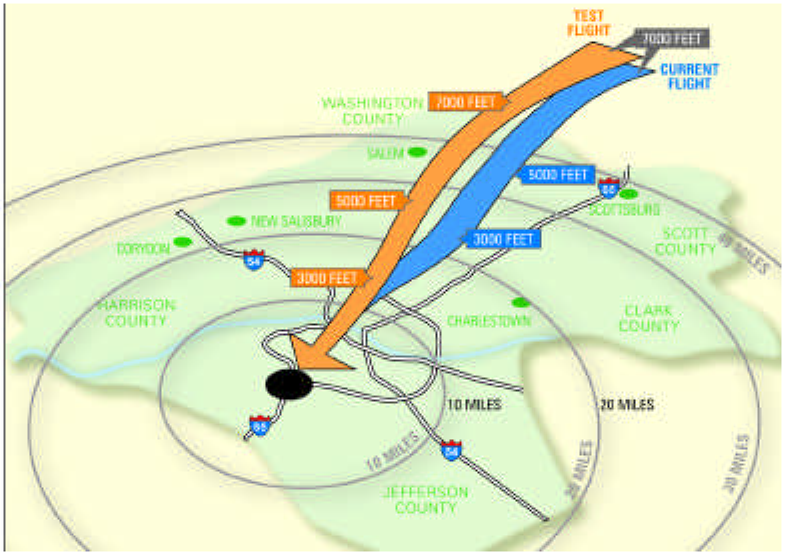
Noise is an ongoing problem at Louisville International Airport in large part because it's the primary hub for UPS, which lands more than 90 large planes each night. The bulk of these landings occur between midnight and 2 a.m. when other background noise is low and residents in surrounding communities are trying to get to sleep or have just fallen asleep—the period, experts say, when it is easiest for someone to be awoken by noise. In a standard approach, the plane is brought down in stages—descending and leveling off several times before landing—with the final level flight segment being only

3,000 feet above the elevation at the airport. Each time an aircraft descends to an intermediate altitude and levels off, thrust must be applied to maintain level flight. And, increasing thrust increases noise. The resulting noise impact on the ground is even greater in communities such as those in southern Indiana where the nearby residential elevation is more than 850 feet higher in relation to the local runways than the residential elevation in Louisville.

Our experimental procedure addresses both the thrust and elevation issues by keeping planes higher longer and then bringing them down in a continuous descent. The aircraft are quieter, both because they are operating at reduced thrust levels and because they are higher as they pass over the affected communities. Calculations indicated that the new procedure would reduce noise from about 69-70 decibels to 62-63 decibels, a significant difference. Because we were examining identical airplanes equipped with identical engines during the same time period, we eliminated variables that could potentially corrupt the noise measurements. And, because we had a complete picture of what the pilot and airplane were doing, and what the noise level was on the ground, we could look at most of the issues associated with how good our predictions were (in terms of both aircraft performance and noise impact). Additionally, we could determine how easy it is to fly this type of procedure.

THE AIRCRAFT ARE QUIETER BOTH BECAUSE THEY ARE OPERATING AT REDUCED THRUST LEVELS AND BECAUSE THEY ARE HIGHER AS THEY PASS OVER THE AFFECTED COMMUNITIES.

Our flight tests occurred during a two-week period beginning on October 28, 2002. For eight nights, two UPS Boeing 767 aircraft on their way to Louisville from West Coast cities were selected (once all aircraft were airborne) to participate in the flight test based on their scheduled arrival time in Louisville. Both aircraft needed to be close enough in the sequence so that the weather conditions would be the same during both approaches. One 767 was instructed to perform the standard approach, which involves a series of descents



Standard flight paths at Louisville (blue) involve a series of staggered descents producing significant noise from multiple thrust increases and landing-configured aircraft systems. The test past (orange) keeps aircraft higher, longer. (Drawing adapted from a Convington Journal Illustration by Mike Covington)

and leveling-off. The other 767 was instructed to perform our CDA continuous-descent procedure: descending on a two-degree flight path angle and then a three-degree instrument landing system glide slope on the final approach course. The performance of the aircraft, pilots and flight management system were measured using two separate systems: the aircraft tracking system installed at Louisville as part of an FAA technology demonstration project and the onboard flight data recording system—the same system used for accident investigations. The noise impact was measured using 14 microphones set up at seven locations (two microphones per location) throughout noise-impacted communities in southern Indiana.

Results of the flight experiment were released in an MIT International Center for Air Transportation Report in May 2003. They show that the CDA procedure reduces noise between three and six decibels at the measurement locations—in line with our predictions—and that there would be significant noise benefits for residents living approximately 10 to 30 miles from the end of airport runways if this approach were widely employed. For reference, a three-decibel difference is noticeable to the average person, while a reduction of 10 decibels is perceived as a 50 percent reduction in noise. Another advantage of the CDA procedure is that it is more fuel-efficient. Since the planes were spending more time at higher altitudes in less dense air, and less time in fuel-wasting slow flight configurations (e.g., flaps down) aircraft performing the CDA used approximately 500 pounds less fuel than aircraft performing the standard approach procedure.

Interest in our procedure is growing rapidly as word travels of the success of our experiment. The CDA procedure will soon be tested at other airports. Now that significant noise reduction has been demonstrated, the next step is for airports, airlines, and air traffic controllers nationwide to incorporate these procedures into daily operations. Our research team is busy designing cockpit displays and air traffic controller tools to enable its widespread introduction.

John-Paul Clarke, an associate professor of aeronautics and astronautics in the MIT Aeronautics and Astronautics Department, holds S.B., S.M. and Sc.D. degrees, all from MIT. His areas of specialization and research interest include air transportation systems, air traffic control, airline operation, and the environmental impact of aviation. He may be reached at johnpaul@mit.edu.

The DSCS III B6 U.S. Air Force communications satellite is pushed spaceward this past August atop a Delta IV Medium rocket. This satellite will provide defense officials and battlefield commanders secure voice and high data rate communications. (Boeing Photograph)

It's Coming — A Paradigm Shift
COMMUNICATION SATELLITE DESIGN

by Eytan Modiano

Most existing communications satellites were designed for voice and video transfer and have a difficult time handling the unique demands of Internet and other emerging types of data traffic. Design of their successors requires a paradigm shift from current technology.

Nowadays, we take the availability of worldwide communication for granted; communication satellites bring us live coverage of events from around the world and undersea fiber-optic cables are used to provide global telephony service. However, as recent as the 1950s transatlantic communication was limited to a few dozen voice circuits and real-time communication with much of the rest of the world was not possible. The concept of man made satellites provideing global communication coverage was first envisioned by Arthur C. Clark in his seminal article "Voices from the Sky" (Wireless World, October, 1945). He described a satellite in synchronous orbit providing communication relay services within any two points on the hemisphere and a constellation of three such satellites for providing global coverage. Clark argued that using a satellite in synchronous orbit would be more cost effective and provide much better coverage than alternative terrestrial communication techniques.

EARLY DAYS

Thirteen years later, the first communication satellite, Score, was launched and used by President Dwight D. Eisenhower to broadcast a prerecorded Christmas message around the world. That early experiment was followed by a number of experiments with communication satellites in the early 1960s that provided early glimpses of the Global Village, including televising parts of the 1964 Tokyo Olympic Games. Later in 1964, agreements were signed that created the International Telecommunications Satellite Organization. Shortly afterwards, the first INTELSAT satellite, Early Bird was launched to provide commercial satellite service. Early Bird, had the capacity for 150 telephone circuits and an additional 80 hours of television broadcast. Early Bird was followed by numerous other satellites that provided worldwide telephone and television service. Today, hundreds of communication satellites are used to provide a variety of services, from military communications to voice telephony, television broadcasts, and Internet access.

CURRENT COMMUNICATION SATELLITES ARE NOT EFFICIENT TRANSMITTERS OF "BURSTY" TRAFFICE LIKE INTERNET DATA

VITAL ROLE IN DATA DELIVERY

Satellite networks play an important role in data delivery. They are very effective at broadcasting data over large geographic locations, and are an effective means for reaching remote locations lacking in communication infrastructure. Satellite networks are critical to our national interests both for military and civilian applications. The military depends on satellite communication for robust and reliable communication in hostile environments. On the civilian side, many rural locations, out of the reach of fiber-based networks, depend on satellites for access to high data rate communication services. As our world continues to progress toward globalization, satellite networks will continue to play a critical role in providing a rapidly deployable, reliable and affordable communication infrastructure.

However, present day satellites are limited in their ability to provide high data rate communication services due to the limited availability and high cost of satellite resources such as power, energy, and frequency bands. Moreover, current communication satellites were designed almost exclusively for supporting stream traffic such as voice, video or bulk data transfers, and are not efficient for the transmission of "bursty" data traffic such as Internet traffic. With data traffic constituting an increasing fraction of the demand for communication services, future satellite systems must be designed to effectively support emerging data applications. Doing so requires a paradigm shift from traditional circuit switched technology, used for voice communication, to packet switched technology, used in data networks. With support from NASA and the Department of Defense, my research group in the Aeronautics and Astronautics Department and the Laboratory of Information and Decision Systems is working to address these important issues. Our research efforts are aimed at significantly increasing the data delivery capacity of satellite networks through the use of efficient resource allocation and protocol designs coupled with the appropriate hardware designs.

Traditionally, the functions of a data network are divided into layers where each layer operates independently. For example, the physical layer is responsible for transmitting bits over a communication channel; the link layer is responsible for transmitting packets over a link; the network layer is responsible for routing packets across the network, and higher layers are responsible for end-to-end data delivery. The layered approach simplifies network operations, but often results in degraded performance. In order to make satellite-based networking technologically and economically viable, the architecture of future satellite networks must be optimized across the different layers of the protocol stack. Protocols for satellite networks must be designed to take into account the unique characteristics of satellite systems such as long propagation delays, limited energy and power, relatively high channel error rates, and time-varying channel conditions. In what follows, we discuss some of our recent accomplishments in the area of resource allocation and protocol designs for satellite networks.

MAXIMIZING DATA THROUGHPUT

An important problem that we are addressing involves the transmission of information from space to earth ground stations. These data may be gathered in space (e.g., weather, surveillance or space exploration images) or simply data that are being relayed from the ground through a satellite network. The information gathered in space must be transferred to one of multiple ground stations located at different geographical locations that can be reached by routing the data to a satellite that has the desired ground station in its view.

The choice of which ground station to transmit the information, to and along which route, is governed by available resources along the route, the utilization of the route, and weather conditions that may affect the link quality. This problem is complicated by the fact that the data can be delivered to one of multiple ground stations, and that modern day satellite systems employ narrow antenna beams for communication where each beam covers a different geographical location on the ground. The channel quality for each of the beams may be vastly different due to local weather conditions.

Two natural questions arise: first, routing, namely, to which beam should the data be transmitted; and second, how to allocate the satellite's transmitters to the different downlink beams and how to optimally allocate power to the beams. Our main contribution in this area has been the optimal solution to the joint problem of routing and power allocation. We developed a joint routing and power allocation algorithm that maximizes the satellite network's overall data throughput. The algorithm makes routing and power allocation decisions based on the number of packets in the buffers corresponding to the different beams. The optimal algorithm allocates more power to beams with more packets in their corresponding buffers; and packets are routed to the beam with the fewest packets (i.e., the least congested beam). A nice feature of the algorithm is that the solution to the routing and power allocation problems can be decoupled. That is, the routing decisions can be made independently of power allocations. However, it is interesting to note that the optimal physical layer power allocation must take into account network layer buffer occupancy. This goes in contrast with the traditional layered view of network protocols; where functions at the different layers are decoupled.

OPTIMAL ENERGY ALLOCATION

A related problem that we are addressing is that of energy allocation and admission control. Typically, a communication satellite is equipped with solar panels that gather energy from the sun to be used for satellite operations. Since, at times, the satellite may not be in view of the sun, they are also equipped with rechargeable batteries to store energy. However, with a limited battery capacity, efficient use of satellite energy is critical. In a communication satellite, downlink transmissions consume a large portion of the satellite's energy. It is therefore important to make prudent decisions regarding the transmission of data by taking into account the amount of energy available onboard the satellite as well as anticipated future demands for energy. Due to energy limitations, the satellite may not be able to serve all of the requests that it receives. Moreover, some transmission requests may consume more energy than others and different customers may offer varying levels of payment for service. Therefore, our objective is to select the requests to be served that maximize overall revenue. Towards that end, we developed a Dynamic Programming formulation for deciding which requests to serve based on available energy onboard the satellite, future energy inputs from the solar panels, as well as the expected requests for future service. We are able to show that the DP value function is a concave function of available energy, and obtain solutions for the optimal consumption schedule by solving the DP recursion in a computationally efficient manner. Our results indicate that expected revenue can be increased by more than a factor of two when compared to the commonly used greedy algorithm that chooses to serve requests as long as energy is available. This new approach can have a significant impact on the operation of future satellite data systems, as it will allow operators to make service decisions that maximize their revenue.

EFFICIENT PROTOCOL DESIGN

Perhaps the most critical challenge to increasing the transmission capacity of satellite-based networks is the design of protocols for communication over a hybrid network that consists of both space and terrestrial components. Most terrestrial networks today use the Transmission Control Protocol as a transport layer protocol. TCP employs a congestion control scheme that is based on end-to-end windows. That scheme assumes that lost packets in the network are a result of congestion, decreasing its effective transmission rate in response to lost packets. In a satellite network, where packet losses are likely to be due to transmission errors, this response is inappropriate and significantly reduces throughput by as much as 90 percent. Much research has gone into developing new protocols that would be more effective than TCP when used over satellite links. Unfortunately, the telecommunication industry is reluctant to make significant changes to Internet protocols; hence progress in this area has been painfully slow.

THIS NEW APPROACH CAN HAVE A SIGNIFICANT IMPACT ON THE OPERATION OF FUTURE SATELLITE DATA SYSTEMS, AS IT WILL ALLOW OPERATORS TO MAKE SERVICE DECISIONS THAT MAXIMIZE THEIR REVENUE.

Eytan Modiano says that the greatest challenge facing communications satellite network developers is designing protocols for communications over networks that include both earthbound and orbiting components.

As a result, satellite systems often employ satellite specific protocols, that operate beneath TCP, for improving performance over satellite links. For example, link layer retransmission protocols are used to eliminate packet errors and media access control protocols are used for efficient sharing of the satellite channel. Our current research explores the interaction between TCP and these lower-layer protocols so that protocols can be designed for efficient joint operation. For example, TCP relies on a timeout mechanism to determine when to retransmit packets and when to activate flow control. The presence of a link layer retransmission protocol can adversely impact TCP's behavior by inadvertently triggering a TCP timeout due to a link layer retransmission. In order to better understand such interactions, we developed analytical models for the performance of TCP in the presence of link layer protocols. These models allow us to better design the satellite protocols so that overall system performance is significantly improved.

FUTURE OUTLOOK

So far, our research has been supported by NASA and the Department of Defense. NASA's interests in satellite communications are clear, as satellites will continue to play a critical role in NASA's space exploration missions. Similarly, DoD continues to rely on satellite communications for both battlefield communications as well as providing a communication infrastructure during deployments in remote or hostile locations.

Perhaps the greatest opportunities for satellite-based networks are in the commercial marketplace. Today, most locations in the world are out of reach of a broadband communication infrastructure. A company that wishes to open a new facility in a remote location in Mexico or China may have to wait years before it can obtain high data rate connectivity. Such delays impede and prevent economic development. Even in the United States most homes cannot receive high data rate Internet access because they are not within proximity of high-speed infrastructure. Satellites are in a unique position to provide these services for very much the same reasons outlined in Arthur C. Clark's 1945 article. Satellites can provide rapid and global connectivity and can be much more cost effective and practical than a terrestrial-based infrastructure. Key to the success of future satellite systems is the ability to develop architectures and protocols that dramatically improve network capacity at reduced costs.

Eytan Modiano is an associate professor in the MIT Aeronautics and Astronautics Department and Laboratory of Information and Decision Systems. He has a bachelor's of science in electrical engineering and computer science from the University of Connecticut, a master's of science from the University of Maryland, and a doctor of philosophy in electrical engineering from the University of Maryland. His research interests include data communication, satellite and hybrid networks, and high-speed networks. He may be reached at modiano@mit.edu

Manuel Martinez-Sanchez observes the operation of a Hall Thruster electric rocket engine through the viewing port of a vacuum chamber in his MIT lab.

Space electric propulsion:
IT'S BEEN A LONG TIME COMING

by Manuel Martinez-Sanchez

In the days when mission success was a higher priority than mission cost, electric propulsion for spacecraft was relegated to the back burner. But with today's budget constraints, mission proposals that don't include EP are at a disadvantage.

The notion of using electromagnetic forces instead of chemical reactions for propulsion through space is almost as old as rocketry itself. Ernst Stuhlinger, of the Werner Von Braun team, had it more or less figured out in the 1950s[1]. The motivation, which is still valid today, was that the faster a rocket's jet can be made to go, the less exhaust mass is needed to impart a given impulse to the vehicle, and engineers knew that there is only so much chemical energy per unit mass that can be converted to exhaust speed, even with exotic—and dangerous—chemicals. If external power can be brought to bear, as in particle accelerators, no jet speed limit is apparent, short of the speed of light. Stuhlinger, and others later, also realized that the propellant mass savings due to the higher exhaust speed would come at a cost in power. This means that a compromise must be struck at some moderately high speed, of the order of several tens of km/s, depending on mission details. Even this is several times higher than the 4-5 km/s available chemically, and can lead to very large mass savings for ambitious space missions. Since electric power is limited onboard spacecraft, only small thrust forces can be produced, but this can be done over hundreds of days.

Despite these early insights, electric propulsion (EP) was slow to reach the application stage. Design conservatism played an important part in this delay, and was the deciding factor as long as mission success was more important than mission cost. With the arrival of commercial space as well as constrained NASA and Air Force budgets, the picture has changed, and we are currently witnessing a rapid transition to where mission proposals not featuring EP are at a serious competitive disadvantage. It has also helped that a few high-profile EP missions have been successful, like Deep Space 1 (NASA), and, more in the background, a variety of large communications satellites in geostationary orbit. There used to be an old saying that EP was, and would always be, the technology of the future. The future is now.

My own involvement with EP research goes back about 20 years. It started as an outgrowth of earlier work on other applications of plasma physics (MHD power generation), and remained theoretical or conceptual until the recent acceleration of application interest. At this point, the Space Propulsion Laboratory (12 graduate students, one staff scientist, one post-doc and me) tackles a variety of problems ranging from computational plasma simulation to laboratory performance measurements (Table 1). The range of skills required for this work overlaps traditional aero-astro topics (fluids, thermodynamics, electronics) with science topics (plasma, physics, electrochemistry). Lately, we are also making incursions into the nanotechnology world—more later. Not surprisingly, this attracts a somewhat different breed of students, a bit more curious about the physical world than the average aerospace graduate, but still interested in engineering and design.

TOPICS	STUDENTS	STAFF	COMMENTS
Colloid Thrusters	Louis F. Velasquez (D) Jorge Carretero (D) Jose Lopez-Urdiales (M)	Dr. Paulo Lozano	Colloid and Ion physics (E,T) Microfabrication of arrays (E) Theory, Porous Feed (E,T) Bipolar Thrusters (E)
Hall Thrusters	Noah Warner (D) Kay Sullivan (D)	Dr. Oleg Batischev	Numerical simulation (T) Experimental measurements (E) Numerical simulation (T)
Plasma Plumes	Shannon Cheng (D) Murat Celik (D) Mark Santi (M)		Numerical simulation (T) Simulation, Physics (T) Numerical simulation (T)
Space Electrodynamic Tethers	Jean-Benoit Ferry (M)		Numerical simulation (T)
Low Thrust Trajectories	James Whiting (M)		Optimization (T)
Instrumentation	Jacob Mirczak (M)		Thrust microbalance (E) Plasma Probes (E)

Notes: D=Doctoral candidate, M=Master of Science candidate, E=Experimental, T=Theoretical.

Table 1: The Space Propulsion Laboratory (as of 4/03) Director, Manual Martinez-Sanchez

For a closer look at our work, I have selected the two general areas of Hall thrusters (and their plumes) and colloid thrusters. Hall thrusters are plasma devices in which ions are accelerated electrostatically, while electrons are magnetically throttled to increase their probability of ionizing the incoming neutral gas atoms (typically Xenon). Fig. 1 shows the typical coaxial configuration, and Fig. 2 is a photograph of a small (200 W power) engine of this type, operating inside our vacuum chamber. Unlike the more traditional ion engines, Hall thrusters have no grids, and are therefore simpler and more rugged. They are now favored for many near-Earth applications, for which the optimum jet speed (15,000 - 20,000 m/s) matches well their own preferred ion speed.

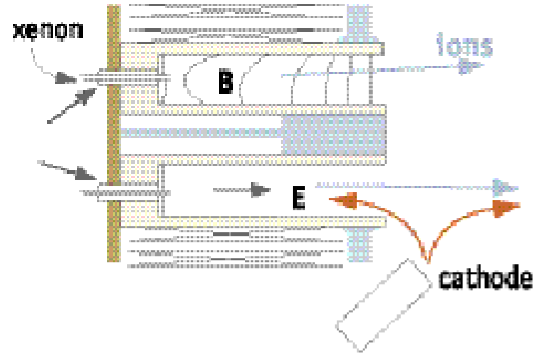


Figure 1: Schematic of a Hall thruster. The annular channel is ceramic lined. A plasma forms near the exit plane, where the magnetic field, B, is maximum. Ions accelerate electrostatically in an electron-neutralized background, and no grids are necessary.

Our contributions in this area have been mainly theoretical, although, as shown in Table 1, we also do experimental work. These thrusters illustrate an interesting phenomenon often seen in research: the physics of simple devices tend to be complex, and vice versa. In this case, since there are no grids to localize the plasma production and acceleration regions, it is the interaction of several highly nonlinear effects that ends up determining where plasma forms, what temperature it attains, how much the plume diverges, etc. The general mechanisms were fairly well understood from the early work in the former Soviet Union, where they were developed since the 1970s, but detailed quantitative knowledge had to await the application of modern computer power, and is still at this time an active research area.

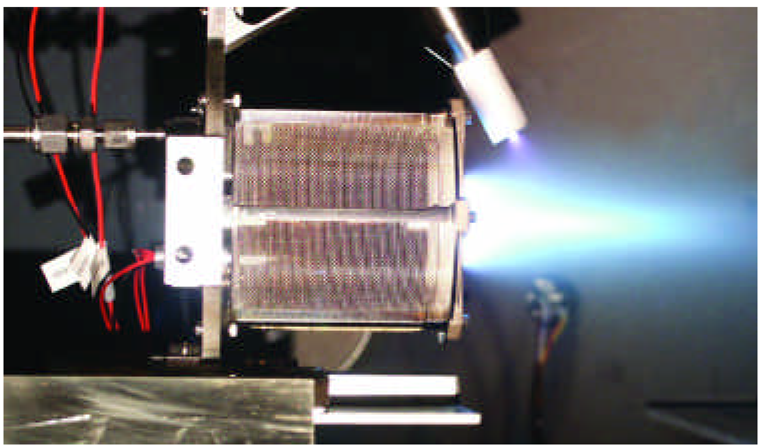


Figure 2: A 200W Hall thruster (courtesy Busek Co. Inc.) in the 1.5X1.5 m vacuum chamber at the SPL. The blue light is mainly from excited Xe ions in the plume. The device at the top is the neutralizing hollow cathode.

We have dealt with this problem using a variety of techniques. One-dimensional models,

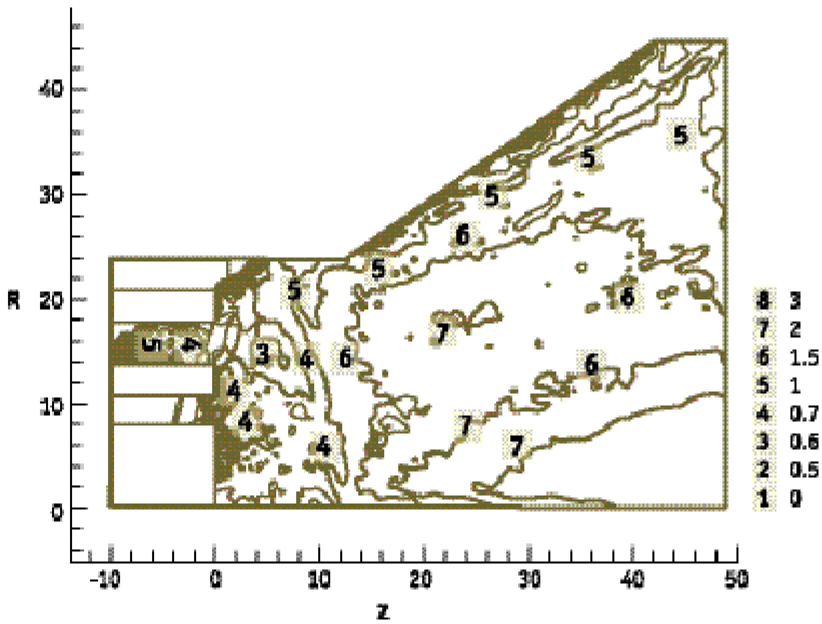
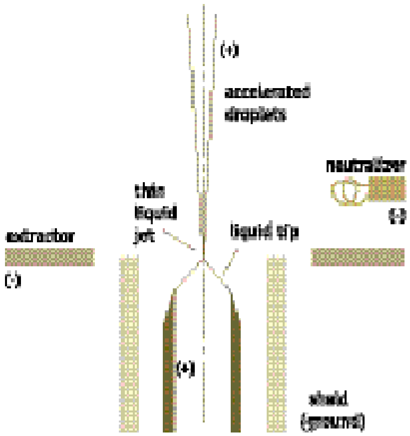


Figure 3: Computed contours of the ratio of parallel to perpendicular electron temperature in a Hall thruster. Deviations from unity indicate the anisotropy due to the strong magnetic field.

pursued in collaboration with E. Ahedo, of the U.P. Madrid[2], have identified and explained the existence of reverse ion flow near the inlet, the nature of the smooth sonic transition near the exit and the general structure of the various zones in the plasma. A very successful model developed by J. M. Fife for his master's thesis[3] included the 2D axi-symmetric geometry, and treated ions and atoms as macroparticles moving about in an electron "fluid," under the influence of constantly updated electric fields. This model reproduced for the first time the experimentally observed current oscillations in Hall thrusters, and explained them as "predator-prey" ionization cycles (electrons as predators, neutrals as prey). It is also in use to generate exit-plane distributions that we then propagate along the vacuum plume using a less detailed, but similar model. An even more detailed description of the plasma physics is embodied in a model developed by J. Szabo for his doctoral thesis[4]. Here, all particles, including the very fast electrons, are tracked as macroparticles, and this allows us to access subtle effects, such as the anisotropic nature of the electron velocity distribution, in the presence of the magnetic field. This model is currently being used to study the changes that occur when operating voltages are increased so as to obtain the higher jet speeds NASA needs for interplanetary applications of these engines.

The thrust generated by Hall devices ranges from 0.01 to perhaps 10 N. This is small, but certain missions now emerging require much smaller, but carefully controllable thrust, down to fractions of a micro-Newton. An example is the gravity wave detection spacecraft



Emitter Diameter:	5-100 μm
Extractor Voltage:	900-3000V
Accel. Voltage:	900-10,000V
Droplet Diameter:	10-50 nm
Ions:	extracted at low flow, high cond.
Fluid:	electrolytic solution or ionic liquid
Polarity:	both possible

Figure 4: Basic principle of operation of a colloid emitter

LISA, where the solar radiation pressure (a few mN) must be cancelled to a 0.1 mN precision. The now familiar plasma accelerator concepts turn out to be inappropriate at these lower levels. A very small plasma needs to be very dense, and so very aggressive. A review of potential mechanisms by V. Khayms[6] led us to propose a revival of a type of electrostatic accelerator—the Colloid Thruster—that had been partially developed around 1970-75, and then abandoned for lack of a mission. Interestingly, in the intervening years, the underlying physical phenomenon—electrospray—was found to be key for the development of precise mass spectrometry of large biomolecules, a development that led to a 2003 Nobel Prize for Dr. John Fenn. Because of this, new levels of understanding of the basic mechanisms are now in hand, and can be put to use for the older space propulsion application.

At a time when exciting new ideas and discoveries are still relatively accessible, we have an active program in colloid propulsion. At its most basic, a colloid single-source thruster (Fig. 4) consists of a capillary tube delivering a saline solution or an ionic liquid to a tip, where an electrode at ~1-2 kV potential deforms the meniscus to a conical shape. A charged nano-jet emerges at high speed from the tip of the cone (Fig. 5) and breaks into tiny droplets charged to near their Coulombic explosion limit. We, and others, have recently found that under very low flow conditions, some fluids can be made to emit pure ions from

Figure 5: Cone-jet structure in the laboratory. The liquid used had low conductivity, which allowed the jet to be large enough to be visible. With more concentrated solutions, the jet diameter is smaller than the wavelength of light and becomes invisible.

the cone's tip. This was known for liquid metals before, but not for organic liquids. We can also emit controlled mixtures of ions and droplets, and this means a very wide range of "jet velocities" for a given fluid and accelerating potential. We have realized that designs can be produced where ions of both polarities are issued at equal rates, thus obviating the need for a separate beam neutralizer.

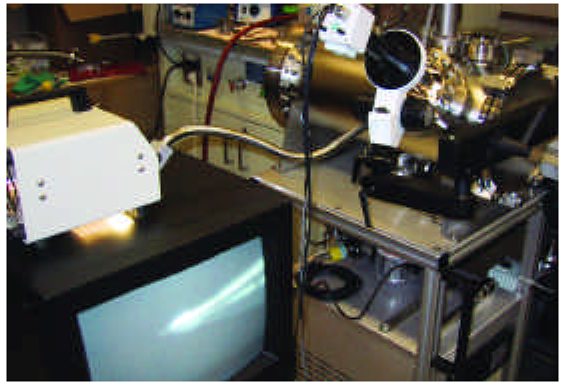


Figure 6: The SPL small vacuum facility for colloid research. The microscope display is showing the tip of a cone-jet emitter in operation.

Much of this colloidal research involves basic physics experimentation (Time-of-Flight spectrometry, energy analysis, etc.), carried out in our small dedicated vacuum facility (Fig. 6). Modeling of the complex fluid mechanisms involved is also helpful, and we have developed accurate predictive models of the cone-jet regime (Fig. 7). And, as the workings of a single source become clear, we are endeavoring to create large arrays of these sources using the silicon microfabrication techniques of the electronics industry (Fig. 8). Success in this work could open the way to modular colloid thrusters that would compete with other EP devices over broad range of power and thrust, with the added flexibility offered by the various modes of operation described above.

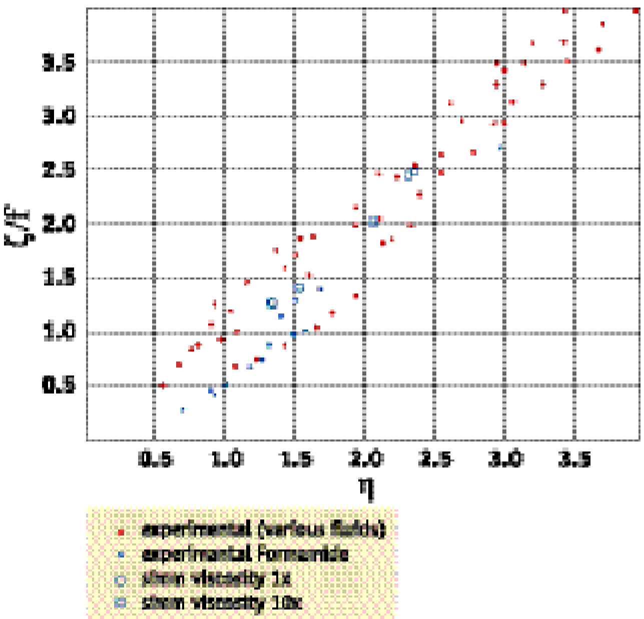


Figure 7: Computation versus experiment. The vertical axis is normalized current per emitter, the horizontal axis is normalized square root of flow rate. The data are from Fernandez de la Mora (Ref 5). (Experimental Uncertainty = +/- 5%

This brief review offers a glimpse of the intellectual excitement the field of space propulsion offers at this stage, when applicability has at last been reached, but maturity is still a long way off.

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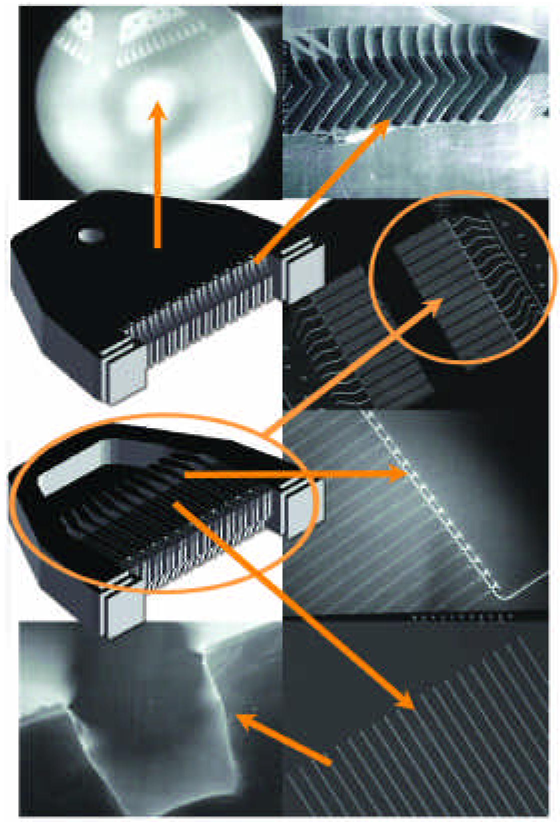

Figure 8: Fabrication details in the linear array engine. The top left panel shows the wafer with several engines after bonding the two halves and annealing.

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Lockheed-Martin's venerable F-16 Fighting Falcon (foreground) and new F-22 Raptor benefit greatly from the application of Lean principles in their manufacture. In the case of the former, Lean manufacturing reduced start-to-finish assembly time by 75 percent. (U.S. Air Force photo)

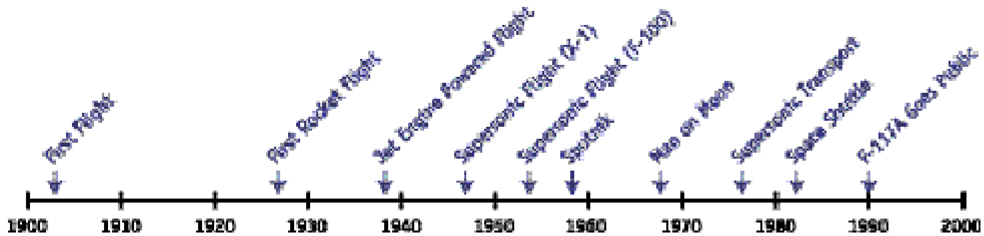
The Lean Aerospace Initiative:
INNOVATING TRANSFORMATION

by Deborah Seifert Nightingale

At 100 years, there have been many celebrations of the rich history of the aerospace industry and many speculations of what the future will hold. The industry is characterized by highly complex technical innovations and spectacular firsts. Recent focus in the industry has been on continuous process improvement. Many aerospace organizations have responded by applying lean principles focused on creating value and eliminating waste.

In the excitement of exploring new territory, pushing limits and expanding boundaries, aerospace systems have focused on technical excellence, striving for higher, faster and farther. The complexity of these systems lies not only in their technical designs, but also in their political and social contexts. These contexts are inextricably linked to the success and failure of many aerospace programs.

Although the Cold War united societal, governmental, and industrial aerospace priorities, the resulting pursuit of performance regardless of cost became readily apparent and unacceptable following the Cold War. Cost overruns and schedule delays brought about more government oversight of defense programs. Commercial aircraft



As indicated by the timeline above, much product innovation has occurred in the 100-year history of the aerospace industry. This focus on improving technology has recently been augmented with an emphasis on process innovation and continuous improvement.

programs became preoccupied with cost, environmental impact, and consumer protection. These shifting priorities presented new challenges with the well-known tag line of "better, faster, cheaper."

Throughout its history, the industry has been on the verge of another "first" many times. This has created and sustained an excitement around aerospace, and intrigued many of us to build our entire careers in the field. Unfortunately, there has been a steadily declining number of new systems in development (more than 90 percent decrease for military aircraft between 1950 and 2000)) and an increasing time to develop these systems (an 80 percent increase between 1965 to 1994). These changes have shifted the knowledge base of the industry from creating opportunities for more technical firsts to lifecycle and process issues focused on the efficiency of developing, delivering, and sustaining systems.

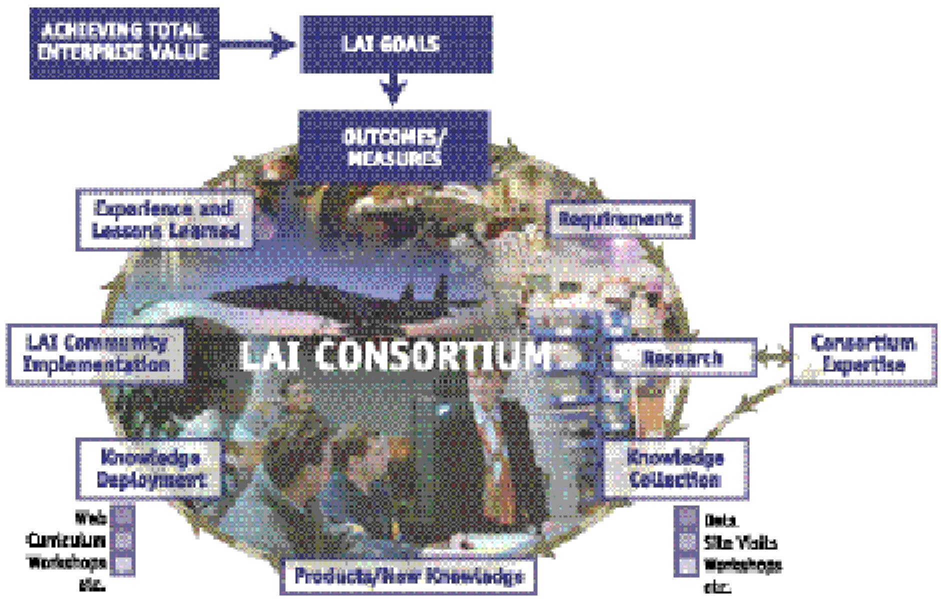
A flagship industry in the United States, aerospace has created many jobs, produced high quality products (of which many derivatives have found their way into the consumer market), contributed to a positive balance of trade, and placed the United States as world leader in aerospace technology. The external environment has continually changed, influencing industry priorities along the way. A central question arises: can the US aerospace enterprise continue a tradition of higher, faster, farther under the pressures of better, faster, cheaper?

RESPONDING TO CHALLENGES

Technological and product innovation will not be enough. In a field where there are arguably dominant designs, competitive advantage shifts to process innovation. Processes as the building blocks of enterprises not only determine how raw materials become assembled systems, but also how information flows and people interact. Considering an enterprise as an integrated entity working towards a common objective, enterprises can be structured as program enterprises, such as the F-16, or as a multi program enterprise, such as Lockheed Martin or the US Air Force Aircraft Systems Center. The Lean Aerospace Initiative addresses a range of challenges facing the aerospace industry today. LAI is a consortium of government, industry, academia, and labor organizations working to transform the US aerospace enterprise through process innovation based on lean principles.

Lean principles originated to improve automobile production at Toyota after World War II in order to compete with Western manufacturers who were poised to enter the Japanese market.. They were characterized and named "lean" during a study conducted by the International Motor Vehicle Program at MIT between 1985 and 1990. Today, five fundamental principles characterize much of lean implementation efforts, starting with focusing on value and ending with pursuing perfection via continuous improvement. These principles have been applied not only in product environments, but in other contexts as well. The functional focus has recently been eclipsed by a holistic enterprise view. This approach, documented in Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative (Murman, et al., Palgrave 2002), suggests, "A lean enterprise is an integrated entity which efficiently creates value for its multiple stakeholders by employing lean principles and practices."

The LAI consortium has approximately 25 member organizations, spanning most sectors of the aerospace industry: military and commercial aircraft, space (launch vehicles and satellites), missiles, engines, and avionics. Funded by both industry and government consortium members, for the past 10 years, LAI has been conducting research relating lean principles to aerospace applications. LAI draws faculty and students from the Department of Aeronautics and Astronautics, the Sloan School of Management, and the Engineering Systems Division at MIT. The current LAI activity at MIT involves approximately 20 students, 10 faculty and 10 staff. The group at MIT plays an essential role in the consortium as the neutral broker and trusted agent in what would be an otherwise competitive situation for many of the members. LAI creates an environment where fierce competitors come together to share best practices,



An ongoing knowledge cycle within LAI maintains the consortium. This community uses a factual foundation of research and practical expertise to direct action-oriented implementation of lean principles.

noble failures, lessons learned, results, and key insights related to lean implementation. The LAI consortium has evolved into a vibrant learning community that leverages an ongoing knowledge cycle.

The LAI knowledge cycle provides a closed loop of research and implementation involving hundreds of consortium stakeholders. Leading edge research is done in a real-world laboratory. The insights, conclusions, and results from this work are developed into useful products that the government, industry, and labor organizations use to transform their enterprises. The tightly coupled relationships in the consortium provide rapid learning and experience cycles and are propelling all of the organizations involved in the consortium forward, significantly accelerating the transformation of the US aerospace enterprise.

CREATING AND FOSTERING LEAN ENTERPRISES

LAI research evolved from early benchmarking studies assessing the applicability of lean in the aerospace context, to focused research diving into specific functional areas such as manufacturing and engineering, to systems-level research moving closer towards the front end of development and acquisition processes, to enterprise-level research addressing interfaces, boundaries, and cross-cutting issues related to achieving total enterprise value. The LAI research program integrates many different areas of expertise, including systems engineering, product development, defense acquisition, supply chain management, organizational behavior, information systems, and others.

LAI activities relate to enterprise transformation, drawing upon analytic and managerial methods rooted in research on enterprise architecture, enterprise change and product development in a system of systems context. Enterprise change captures not only the organizational behavior issues surrounding change management, but also incorporates the structural aspect of aligning a human organization with the processes, the information systems, and the streams of value in the enterprise. A tough problem for enterprise architecting of a multi program enterprise is how to balance the demands of local program performance with enterprise integration and capability development. For example, program enterprises typically generate revenue, but the multi program enterprise typically provides the enabling infrastructures as a service to the programs. In the product development area, recent focus has been on the notion of spiral development, following an iterative process to deliver incremental capability in a relatively short time frame. It has yet to be determined how this is most efficiently accomplished, especially as the complexity of the system and the enterprise increases.

POSITIONING AEROSPACE ENTERPRISES FOR THE NEXT 100 YEARS

Where are the real benefits of this work evident? There are numerous examples of the impact of applying lean principles to process improvement efforts throughout the aerospace industry. The impact scales with the scope of the transformation effort. In a manufacturing example, lean implementation resulted in a new assembly process for the Boeing 777 composite floor beam which took 47 percent less time than the original process. In an integrated implementation between manufacturing and engineering, Lockheed-Martin created a build-to-print center for the F-16 to collocate engineering support on the shop floor, reducing their start-to-finish cycle time for the aircraft by 75 percent. Through an integrated approach between manufacturing and supply chain management, an aircraft engine facility achieved 100 percent on-time deliveries. By incorporating lean principles into program management practices, the Joint Direct Attack Munitions program reduced the entire unit cost by 63 percent. Scaling even further, with a corporate, multi-division, multi-program enterprise implementation, Raytheon realized $300 million FY 2000 bottom line benefits.

It is clear that aerospace enterprises have begun a process of transformation, and that lean ideas have enabled impressive examples of improvements. However, the challenge is to deliver value, not in a single function or a single program, but across the entire enterprise. The potential impact provides the impetus for LAI to pursue transformation of the US aerospace enterprise. LAI tackles intellectually challenging problems in a fast-paced, applied environment.

The author acknowledges Alexis Stenke of the LAI staff for her extensive contributions to this article.

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Sophomores (from left) Nii Armar, Eric Mibuari and Lauri Kauppila participate in a lively turn-to-your-partner exercise, one of the active learning techniques employed in Aero-Astro's Unified Engineering classes.

TEACHING BY QUESTIONING

by Steven R. Hall

I began to rethink how I was teaching and realized that students were deriving little benefit from my lectures even though they generally gave me high marks as a lecturer. So I decided to stop preaching and instead of teaching by telling, I switched to teaching by questioning using a teaching technique I have named "peer instruction." I have been lecturing like this now for four years. During this time the students have taught me how best to teach them. As one student said in a recent interview, "There is the ah-ha! kind of feeling. It's not that someone just told me; I actually figured it out. And because I can figure it out now, that means I can figure it out on the exam. And I can figure it out for the rest of my life."

Harvard Physics Professor Eric Mazur on his development of peer instruction and concept tests, two of the active learning techniques being applied with great success in MIT Aero-Astro.

In 1996, the MIT Aeronautics and Astronautics faculty participated in a strategic planning process, which culminated in adoption of a formal strategic plan for the department in 1998. One of the plan's educational thrusts, which we called "Learning-Based Education," was intended to improve the effectiveness of our teaching. The plan called for the department to gain a better understanding of current scholarly work on learning, especially the learning of science and technology, and to use our improved understanding of learning as a basis for improving our educational process and infrastructure.

The plan led us to adopt active learning techniques in many subjects. Active learning is defined as those teaching techniques that stress students' active involvement in their own learning. There has been a tremendous amount of research in the educational community on the benefits of active learning. The research has demonstrated that in addition to achieving learning objectives related to content, students develop abilities in communication, leadership, ethical decision making, and critical thinking.

One of our biggest successes in implementing active learning has been in Unified Engineering, the set of courses that comprise our sophomore core. In Aero-Astro, the sophomore year is organized around four courses (two in the fall and two in the spring), collectively titled Unified Engineering. Unified has a unique structure, in which five disciplines are taught throughout the year: fluid mechanics, structures and materials, dynamics, signals and systems, and thermodynamics and propulsion. (This year, we will be teaching Computers and Programming, instead of Dynamics, to reflect the increasing importance of information systems in aerospace engineering.) Each discipline has about 40 lecture hours spread between the fall and spring terms, except for Thermodynamics and Propulsion, which has 20. In addition, the students learn aspects of systems engineering and design through a series of interdisciplinary problems, called "systems problems."

Steve Hall displays a Personal Response System infrared transmitter. Students use the devices to respond to questions Hall poses during his lectures allowing him to immediately assess understanding and, if necessary, address unsatisfactory results in real-time.

Prior to 1998, a few Aero-Astro faculty were sporadically using various active learning techniques, such as turn-to-your-partner exercises, in Unified Engineering. In the academic year 1998–1999, one of us began using active learning techniques more extensively in Unified. He used concept tests from the Peer Instruction method advocated by Harvard University Physics Professor Eric Mazur. In this method, lectures are punctuated by brief, multiple-choice, conceptual questions to test student understanding of the material. During 1998–1999, the use of concept tests was sporadic, even in the single discipline using the technique. Nevertheless, student response was quite favorable. Students reported that they enjoyed the learning experience using concept tests, and some felt it improved classroom learning. Moreover, there is anecdotal evidence that the approach improved conceptual learning in Unified.

Inspired by the modest success of active learning in Unified in 1998–1999, the faculty of Unified decided to incorporate active learning techniques more broadly, with all faculty using active learning techniques. During 1999–2000, each of the following techniques was used by one or more Unified instructors:

- concept tests
- turn-to-your-partner discussions
- cold calling
- in-class demonstrations
- reading quizzes at the beginning of the lecture
- muddiest-point-in the lecture cards (“muddy cards”)

All faculty used the muddiest-point-in-the-lecture technique. Three instructors used concept tests or turn-to-your partner exercises.

The use of active learning in 1999–2000 was very successful, as judged by students in the end-of-term course evaluations, and by the faculty in their annual reflective memos. For the academic year 2000–2001, the faculty decided to adopt a more intensive and uniform approach to active learning. All faculty agreed to use concept tests and muddy cards in lectures, which we continue to do.

CONCEPT TESTS

The most successful active learning technique that we have used is the concept test. A concept test is a multiple choice, usually qualitative, conceptual question, given to students during lecture, to test their conceptual understanding as the lecture progresses. In a typical lecture using concept tests, the instructor lectures for 10-15 minutes, and then a concept test is given to assess student understanding of the concept. If most students correctly answer the concept test, the instructor continues with the lecture, knowing that the students have understood the concept.

If incorrect answers predominate, it’s likely that many students have misunderstood the key concept of the lecture. The lecturer has several options at this point. If, say, 15 – 40 percent of the class answered incorrectly, the instructor may instruct the class to work in groups of two to four students. Students are instructed to try to convince their neighbors of the correctness of their answer, and then to answer the question again. The process of explaining the answer to another student, whether the answer is correct or incorrect, can be beneficial to both students. The most obvious benefit is when one student who understands the problem can successfully explain the answer to a second student who doesn't understand. This process solidifies the understanding of the first student, while helping the second student learn the concept. Less obvious is the benefit that comes when students with an incorrect answer explain their answer. The process of verbalizing the answer causes students to carefully reconstruct their reasoning, and often this process causes students to see their mistake. In effect, the process of explaining their answers to one another forces students to become teachers, which is why Mazur calls the techniques "peer instruction."

If most students get the answer right on the first or second try, the lecturer can continue on to the next topic. If a large number of students still have trouble after the second try, then the class has a problem with the concept, and the best approach is for the lecturer to re-explain the concept. Often, the instructor can discern the conceptual roadblock students have by listening to the group discussion during the concept tests. Knowing the difficulty allows the instructor to better address student misconceptions in the remainder of the lecture.

A good concept test has a number of important characteristics. Most importantly, it should be conceptual in nature, and focus on a single concept. It should be multiple-choice, so that responses can be tallied quickly. It should be easy enough to be completed in a few minutes, but not so easy that students don't feel challenged. A typical concept question from the Signals and Systems part of Unified is shown in Fig. 1.The important concept in the question is that the current in an inductor cannot change discontinuously. Therefore, after the switch is opened, the same current that was initially flowing through bulb A must flow through bulbs B and C. Therefore, the correct answer is number 3. Students who fail to grasp this concept often give answer number 2—they incorrectly believe that the voltage across the inductor is continuous. Indeed, some students find it very disconcerting that after the switch opens, the voltage across the

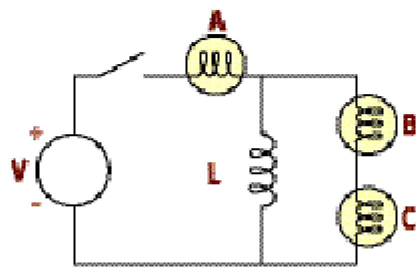

Figure 1. Typical Concept Test.

In the circuit above, the switch is left closed for a very long time, so that A is glowing, and B and C are dark. The switch is then suddenly opened. What happens to each bulb after the switch is opened?

1. All the bulbs are dark.
2. A goes out. B and C initially glow, and then dim. The intensity of B and C is less than the original intensity of A.
3. A goes out. B and C initially glow, and then dim. The intensity of B and C is the same as the original intensity of A.
4. A goes out, and nothing happens to B and C.
5. Nothing happens.

inductor is twice as large as the voltage of the voltage source. This discomfort can be a good thing — it produces a teachable moment, when students are receptive to ideas that challenge their view of the world.

Student responses to the concept tests can be gathered in different ways. Initially, we used flash cards, with students presenting their answers simultaneously. A quick scan of the room is sufficient to determine approximately the rate of correct and incorrect responses. Flash cards are cheap, easy to use, and confidential (since, if students are seated facing in the same direction, each sees only the backs of other flash cards). However, there are a number of drawbacks to flashcards that led us to begin using an electronic response system, the Personal Response System brand infrared system. For example, with flash cards, it is difficult to capture student response for later analysis by the instructors. In a typical classroom installation of the PRS system, each student has a hand-held infrared remote transmitter, much like a television remote control. During a multiple choice concept test, each student indicates his or her answer by pressing a single digit on the remote keypad. An infrared receiver connected to a personal computer collects the student responses, and displays the result in histogram form to the instructor. The electronic system allows students to respond when they are ready, instead of all at once. The system also records the results of each concept test for later analysis.

MUDDIEST POINT IN THE LECTURE

Another active learning technique that we have used with success is the "muddiest point in the lecture" technique, credited to Harvard Professor C. Frederick Mosteller. In this approach, students are asked to take two minutes at the end of each lecture to write the most confusing (or muddiest) point of the lecture on an index card, and hand it in to the instructor (Fig. 2). Some instructors also ask students to identify the most important point of the lecture. These muddy cards, as we call them, serve two useful functions. First, they give students time to reflect on their learning. Reflection is an important activity to reinforce learning, but is not practiced often in the high-pressure atmosphere of an MIT education. Second, the muddy cards provide direct feedback to instructors on problems students are having in class.

Instructors can act on the information in muddy cards in several ways. They can use part of the next lecture hour to discuss common muddy points. Instructors in Unified often use the Web to post responses to questions on the muddy cards. Or, instructors can simply

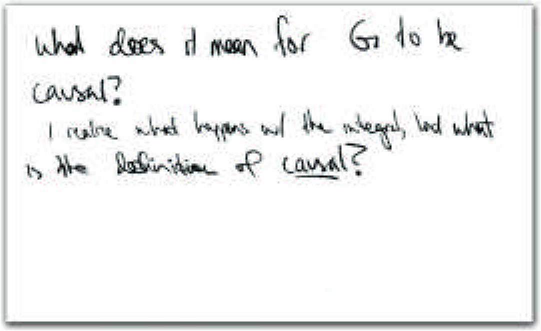

Figure 2. Typical Muddy Card from a student. The card reads, “What does it mean for G to be causal. I realize what happens with the integral, but what is the definition of causal?”

use the information to modify the next lecture, or to modify lectures the next time they teach the subject. No matter how the information is used, most instructors who use muddy cards find them to be an important source of feedback. Several faculty in Unified have remarked that, after seeing the benefits of muddy cards, they will never teach again without using them.

STUDENT REACTION TO ACTIVE LEARNING

Student reaction to muddy cards has generally been favorable. In end-of-term course evaluations of Unified, students have written:

> Every [professor] should post answers to MUD cards. It’s so useful.
>
> What [the professor] did with muddy points, lecture notes and so on was great. If every professor did that, MIT would be the best school anywhere.

From the students’ point of view, the response to the muddy cards provided instant feedback. Perhaps as important was the message that posting summaries conveyed to the students. One student commented that “the [professor] really cared that we understood, he put things on the Web.” The theme of caring was evident in many of the student comments.

When students were asked to comment on the teaching of the course or to compare the active learning techniques to the traditional lecture format, their responses reflected an overall positive attitude towards the active learning techniques. For example, one student described the techniques as “dramatically better than traditional blackboard format.” Others specifically commented on the effect of the active learning techniques on improving their learning and understanding of the content, and in stimulating their thinking and classroom participation. Other students commented that:

> Active learning is also a big plus since it gets students thinking in class instead of just taking in information.
>
> Taking time out to solicit feedback on a regular basis did wonders for my morale and enthusiasm.
>
> Concept questions ... are really great to help my understanding.
>
> Effective use of PRS is an awesome form of feedback.
>
> I think it is very important to observe how other people approach a problem to expand one’s own ability to do so. It also makes the problems more enjoyable when we

work together to figure out all the little nuances involved.

I really enjoy working by teams because that way we can see the different ways of solving a problem. It also helps us learn how to explain our ideas on solving a problem and points out weaknesses in our reasoning.

A few students did not find active learning techniques to be useful. One student described active learning as "irrelevant fluff," while another student believed that it "detracted from class-time" and "did not add to learning value enough." We found that student acceptance of active learning techniques improved when we carefully explained their purpose early in the course, and reinforced that explanation often throughout the term.

The author thanks Ian Waitz, Doris R. Brodeur, Diane H. Soderholm, and Reem Nasr, for their contributions.

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Faculty Profile:
FROM SAILBOATS TO SPACESUITS, ENGINEERING WITH A PASSION

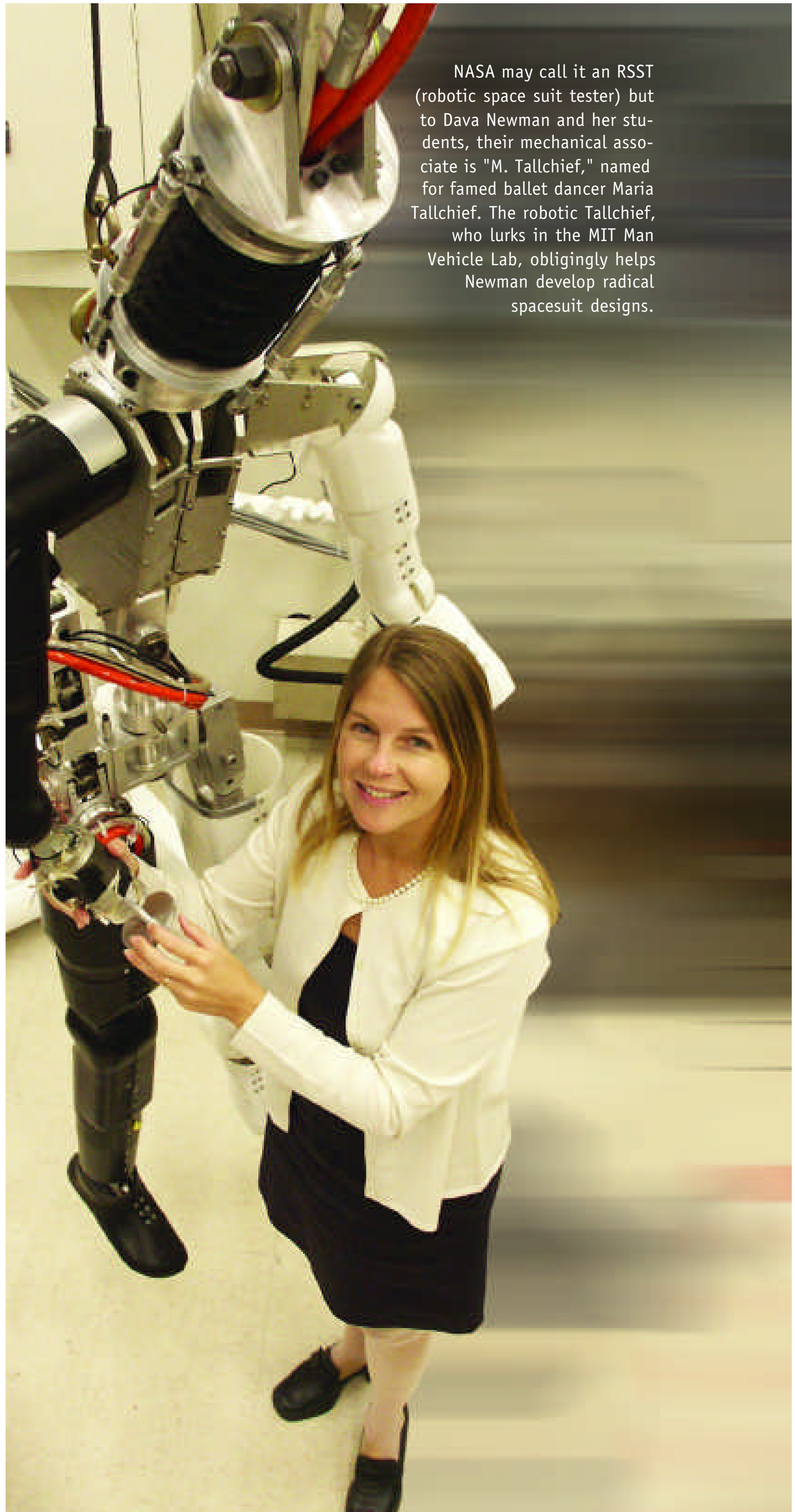
by Lauren Clark

Whether she's battling a disabled boat in the middle of the Pacific Ocean or crafting the next-generation spacesuit, Dava Newman lends a unique energy, enthusiasm and excitement to her research, her teaching and her recreation.

MIT Aero-Astro Professor Dava Newman's recent sabbatical was what you'd expect from an aerospace engineering professor whose twin passions are exploration and teaching. She spent a year circumnavigating the globe in her 13.2-meter sailboat, *Galatea*, stopping en route to teach kids about exploration via sea and space travel.

Though experienced sailors, Newman and her partner Guillermo Trotti faced an unexpected challenge while crossing the Pacific from the Galapagos to the Marquesas islands: *Galatea's* hydraulic steering system failed. The pair spent an entire day hand steering the vessel while engineering a temporary fix for the problem. This included replacing lost hydraulic fluid with extra virgin olive oil from *Galatea's* kitchen.

"This was our Apollo 13! (Fixing the problem with the tools we had on hand, none of which were



NASA may call it an RSST (robotic space suit tester) but to Dava Newman and her students, their mechanical associate is "M. Tallchief," named for famed ballet dancer Maria Tallchief. The robotic Tallchief, who lurks in the MIT Man Vehicle Lab, obligingly helps Newman develop radical spacesuit designs.

designed for the exact task)," they wrote on the Web site that chronicles their 35,000 nautical mile voyage: http://www.galateaodyssey.org.

When Newman wasn't on the open sea, at the helm, or cooking mahi mahi for dinner, she was teaching. She visited middle school and high school classrooms in Puerto Rico, Panama, Australia, Mauritius, South Africa and other locales that span the spectrum of technological and economic development. She educated students in science and technology, geography and exploration, and oral history. With NASA's help, she connected her international students with their counterparts in the U.S. through video links, and organized videoconferences between the students and NASA astronauts and scientists.

One of the goals of her sabbatical was "to excite students about exploration, space travel, and what it takes to get there—science and math," says Newman. Another was to make students around the world aware of how their perceptions are shaped by "where and how they live."

A PASSION FOR TEACHING

Newman's passion for teaching is renowned at MIT. In 2000, she was named a MacVicar Faculty Fellow for significant contributions to undergraduate education. Her course for undergraduates, 16.00: Introduction to Aerospace Engineering and Design, culminates each year in what has become an MIT tradition: a race of student-designed blimps. It has attracted many engineering students — among them a growing number of women—to the aerospace branch of the field.

Professor Wesley Harris, head of the Aero-Astro Department, is a big fan of Dava. "She has a rare mix of energy, vision, technology and policy. These traits are the foundation of the engineer of the future," he says. "Her contributions to this department, the institute and the profession will be profound."

Newman's students say she is highly supportive and persistent in encouraging them to do their best work. Annie Frazer, a graduate student of Newman's working in the Man Vehicle Laboratory, says, "Even though she's always on the go and doing 10 things at once, she's surprisingly laid-back and easygoing."

Laid-back and easygoing, yes, but she's a driven academic and professional, too. She holds a bachelor's degree in aerospace engineering from Notre Dame; a master's in aeronautics and astronautics and another in technology and policy, both from MIT; and a doctorate in aerospace biomedical engineering, also from

MIT. She joined the Aeronautics and Astronautics Department faculty in 1993 and has been an affiliate faculty member of the Harvard–MIT Division of Health Sciences and Technology since 1995. Her research interests include extravehicular activity analysis and astronaut motion dynamics and control. Of her pioneering research in space biomedical engineering, Aero-Astro professor R. John Hansman Jr. says, "Dava is one of the world leaders in experimental studies of astronaut interaction with space vehicles. Her work has had a significant impact on the design and operation of the [International] Space Station."

Interestingly, her studies of space-related human physiology and control had led her into yet another area of research of great importance to the earthbound individuals: the development of assisted walking devices for the physically handicapped.

NEWMAN'S PROJECTS INCLUDE A RADICAL SPACE SUIT, CALLED A "SKIN SUIT" WHICH WOULD APPLY PRESSURE DIRECTLY ON THE WEARER'S SKIN

One of her projects, the Enhanced Dynamic Load Sensors experiment, was conducted aboard the Russian MIR space station. The project involved investigation of the dynamic response inside MIR including disturbances by crewmembers, and investigations of the fundamental consequences of microgravity on living organisms during space flight.

THE RADICAL "SKIN SUIT"

Newman's experiments aboard MIR, the ISS and other research projects are directed toward a long-term goal: NASA's first human mission to Mars. Such an expedition, which, she says could become reality within the next 15 years, could require humans to spend an estimated two years in reduced and zero gravity environments. With this in mind, Newman's work explores human performance in the weightless environment of deep space and on the surface of other planets, and applies the resulting data to the development of devices that will sustain astronauts' health and increase their comfort—both inside and outside space vehicle and habitats.

One such device is a radical new space suit that Newman calls a "bio-suit" or "skin suit." As the name implies, astronauts wearing the suits would no longer resemble Bibendum, the Michelin Man; they'd look more like speed skaters.

Unlike today's bulky, cumbersome compressed-air spacesuits, the bio-suit garment itself would apply pressure directly to the astronaut's skin, simulating

Earth's atmosphere. It would allow astronauts much greater mobility and dexterity, not only through its sleek design but also through small-scale, electro-mechanical augmentation of movement. It would truly be a spacesuit for exploration—a must for extensive geologic surveys of the Martian landscape.

Moreover, donning and doffing the bio-suit would be less arduous than with current spacesuits, which Newman calls "the world's smallest spacecraft." Actually, "donning" and "doffing" aren't the right words. "Electrospinlacing" and "melt-blowing" are more like it. In the former process, the suit would be, in effect, painted on. In the latter, astronauts would be "shrink-wrapped."

Newman admits that the bio-suit project, still in the conceptual phase, represents "some of my farthest-reaching ideas." But she contends, "Spacesuit design shouldn't look like everything you've seen before."

FROM FAR-REACHING TO PRACTICAL

As research at MIT has proven time and again, far-reaching ideas can lead to practical applications. In Newman's case, the mobility research for the bio-suit project led her, graduate student Joaquin A. Blaya, and colleague professor Hugh M. Herr, a lecturer in MIT's Artificial Intelligence Lab, to develop a prototype prosthetic device that restores a nearly normal gait in people with "drop foot." Drop foot a common pathology that often follows a stroke, involves a paralysis of the leg flexor muscles making it virtually impossible for an individual to walk.

Whether circumnavigating the globe in a sailboat, designing spacesuits for Martian exploration, or helping people walk, Newman has a passion for her work that "really is contagious," says Blaya. Frazer agrees. "It's not until you meet someone like Dava that you realize what kind of potential we all have."

Lauren Clark is a freelance writer who has worked in the MIT Aeronautics and Astronautics Department.

Alumni Profile:

FROM FLIGHT OF FANCY TO FANCY FLYING

by Dick Dahl

Aero-Astro alum Tom Imrich first experienced big jets at the controls of a simulator he cobbled together at MIT from a surplus cockpit mockup, an old computer and salvaged CRTs. Thirty years later, he can fly touch-and-goes in 777s.

The photo on the wall inside MIT's Building 10, the one of a guy sitting at the controls of an airplane flight simulator, is a source of nostalgia for Capt. Thomas Imrich. But it is more than just a warm memory for Imrich, today the chief research pilot at the Boeing aircraft company in Seattle. It is a document of historical significance.

Imrich took the photo in 1970, when he was a 23-year-old graduate student in the Aeronautics and Astronautics Department working toward a master's degree and part of an informal but active subculture of flying fanatics at MIT. Imrich was a flyer from a flying family when he came to Aero-Astro as a freshman in 1965 and the student in the photo, Jack Howell, was an Air Force veteran who flew F-4s in Vietnam.

Reminiscing about the photo and his student days recently from his home in Mercer Island, WA, Imrich recalls that MIT was providing him the thorough scientific grounding that he had sought in preparation for a career in aeronautics. But as a licensed pilot, he felt something was missing.

"The MIT education, while terrific, was very theoretical," he says. "There were no throttles or sticks or instruments."

The young Tom Imrich knew some people at Boeing, and they told him that the company no longer had use for several cockpit mockups it had built for the recent-

Tom Imrich stands with the Piper Seneca he flew in formation with the Boeing S-307 Stratoliner (in the background) so Boeing photographers could record one of the historic airliner's final flights. The 63-year-old plane, the last of its kind, has since been delivered to the Smithsonian.

ly cancelled 2707 supersonic transport. Arrangements were made with Boeing for donation of one of the mockups, which was flown from the manufacturer to Hanscom Air Force Base in Bedford, MA aboard an Air National Guard C-130 and then trucked to MIT. "We had to knock down a cinderblock wall in Building 35 to get it in," says Imrich. Together with grad student Bob Anderson, and Division of Sponsored Research staff member Mark Connelly he combined an old Adage graphics computer with some salvaged CRTs to transform the mockup into a home-made 707 simulator.

While the story is a pleasant tale of youthful pluck, Imrich points out that it is more than that because the simulator provided useful research outcomes for the aeronautical world. He was the first of several students who used the simulator for their theses. Imrich's project used the machine to examine computerized air traffic display, then in its infancy, and the forerunner of today's universal traffic alert and collision-avoidance system.

"I strongly support the department's new dedication to the 'hands-on' approach," says Imrich referring to curriculum changes in the last few years that stress design and workshop-based projects as well as the learning of engineering science. He's a big fan of the department's new syllabus and curriculum based on conceiving, designing, implementing and operating aerospace and related engineering systems. "I wish we had more of that when I was there. But we always found a way. We had no flight deck, so we built one. We had no soaring club, so we started one. No one told us things couldn't be done or that they might be hard, so we just did it."

Imrich says both the education he received and the people he met during his years with MIT have played an instrumental role his career. "MIT gave me the solid engineering technical foundation I needed. And, I continue to interact with former classmates and faculty on issues of common interest." Imrich stays in close contact with the Aero-Astro Department, often agreeing to participate on committees and review boards. He also is occasionally found back in the classroom, speaking to students about his career.

Imrich considers himself fortunate for having come of age in the early part of what he calls "the modern jet era," placing him in a position to experience a variety of firsts in aircraft developments and safety improvements. His post-MIT career started with an active-duty stint in the U.S. Air Force, where he was involved in groundbreaking work on windshear avoidance, an expertise that drew the attention of the

Federal Aviation Administration, which hired him in 1976 to work in its Office of Systems Engineering Management in Washington, D.C. He stayed at the FAA, where his work in several leadership roles focused on improving flying safety, until 2001, when he joined Boeing.

As Imrich explains, his work at Boeing, like that at the FAA, is still essentially aimed at improving safety for the flying public. But now operational efficiency is also part of his charge.

"My principle role at Boeing, serving as chief research test pilot, is to deal with the cross-model features of our product line and new aircraft to help develop and implement systems that are important for our customers to fly these airplanes in the evolving air-space system, and applying new technology that brings benefit to our customer base," he says.

What that means for Imrich is well over 300 hours a year flying huge Boeing aircraft. Recently, for example, Imrich has been piloting 737s and gauging the effectiveness of a new autopilot system that he says will "significantly improve low-visibility landing capability."

Although his primary work has dealt with Boeing's existing product line, he says that he will be devoting more time in coming months to the "experimental" division and continuing development of the model 777.

In addition, part of Imrich's job is to take part in the ongoing certification of every airplane that comes off the Boeing production line. Each plane is test flown, during which every aspect of the airplane's operation — including inflight engine shutdown and restart — is tested.

Not all of Imrich's work involves testing big jets. This past September he had the enjoyable task of piloting a small prop plane in formation with the last remaining 1940 Boeing S-307 Stratoliner while photographers aboard his aircraft recorded the airliner in action. The historic aircraft, which Boeing restored, has since been delivered to the Smithsonian.

Among his career achievements, he counts his work with FAA in developing U.S. and international criteria for low-visibility landing as a particular highlight. In addition, the TCAS technology that he first studied on the old MIT flight simulator that he and his friends created long ago has played an ongoing role in his career. Much of his work at FAA dealt with TCAS.

As Imrich looks back to how the world of aviation has changed during his career, he marvels. "The ability to massively integrate flight-deck functions and features and connect them in important ways that improve both safety and efficiency are vastly better. Our ability to communicate with different parts of the airport and to the external world is vastly different. We're now in the process of connecting smart airplanes with smart ground systems to fly effectively and efficiently."

Inevitably, evolving aeronautical technology is changing the role of the pilot. While there's no doubt that Imrich loves the throttles, sticks, and instruments as much as he did when he was an MIT student with his hands on a flight simulator, he's also excited by the future of piloting. While pilots traditionally have had to focus their attention on such matters as flying at a certain level for hours on end, now smart machines can take care of that job.

Now the pilot can elect to offload that task and have the aircraft do that itself while the pilot focuses on the bigger picture of 'Where am I going?, What's the weather?, What are the constraints on the operation of my vehicle to best match airport connecting flights?, If the weather is bad there, where would we rather be for the convenience of our passengers and for the airline schedule?' And so forth."

As Boeing's chief research test pilot, of course, Imrich will continue to keep his hands on throttles and sticks, which makes him happy. But he says that he takes even more satisfaction from the purpose of his work. "The fun and the excitement of flying will always be there," he says. "But I think the bigger picture for me is helping make things better, make them safer, and operate aircraft in ways that provide services and capabilities that weren't available before. It's a tremendously interesting activity. It's a lot of fun."

As Boeing's chief research pilot, Tom Imrich's 'office' is the cockpit of a wide variety of passenger aircraft.

And, by the way, Tom isn't the only Imrich with a connection to Aero-Astro. Younger brother, Steve, who holds a master's in architecture from MIT, was the main designer and project manager for the recent creation of Aero-Astro's Learning Laboratory and the renovation of Building 33, MIT's Guggenheim Aeronautical Laboratory.

Dick Dahl is a freelance writer who lives in Somerville, MA.

LAB REPORT

Within the Aeronautics and Astronautics Department are a number of laboratories performing landmark aerospace research and development. As we note in Aero-Astro's introduction, the articles in this publication detail only a few of our projects. Here, we offer a brief tour of our labs and a glimpse at some of their fascinating projects.

AEROSPACE COMPUTATIONAL DESIGN LAB

The Aerospace Computational Design Lab'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 L. Darmofal, Mark Drela, Bob Haimes, Ali Merchant, David Venditti, and Karen Willcox. Jaime Peraire directs the lab. *Visit ACDL at http://raphael.mit.edu/*

CHARLES STARK DRAPER LABORATORY

Building on a legacy of technological innovation and a reputation of solid engineering performance, Draper Laboratory is focused on solving the challenging technical problems that our nation faces as it enters the 21st century. To this end, Draper's engineering organization supports the technology development to business areas and develops new technologies for a wide variety of applications through internal investments and through the Laboratory's Independent Research and Development efforts.

More than 600 technical staff and more than 60 graduate students strive to ensure that the laboratory will continue to be recognized as the nation's premier laboratory focused on the measurement, analysis, and control of complex, dynamic systems. Draper has, for example, developed techniques for control of the flexible and variable structure of the International Space Station. Draper is also applying its core competencies in guidance, navigation, and control and advanced microelectronics to a wide spectrum of applications such as information systems, biomedical engineering, and commercial space systems. *Visit the Draper Lab at http://www.draper.com.*

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 H. Epstein is the director of the lab. GTL faculty and research staff include Mark Drela, Fredric Ehrich, Yifang Gong, Edward M. Greitzer, Gerald R. Guenette Jr., Stuart Jacobson, Jack L. Kerrebrock, Ravi Khanna, Carol Livermore, Ali Merchant, Nori Miki, Manuel Martinez-Sanchez, James Paduano, Zoltan S. Spakovszky, S. Mark Spearing, Choon S. Tan and Ian A. Waitz. *Visit GTL at http://web.mit.edu/aeroastro/www/labs/GTL/index.html*

INFORMATION CONTROL ENGINEERING

Information Control Engineering researches topics related to aircraft and spacecraft control, large space structures, active stabilization of flow through compressors, reduction of vibrations in helicopters, detection of failures of control system components, and other subjects of interest in aeronautics and astronautics. Theoretical research is pursued in such areas as estimation and system identification, failure detection and isolation, control systems which are robust to plant model uncertainties and nonlinearities, and autonomous systems. ICE Aero-Astro faculty include John J. Deyst Jr., Eric M. Feron, Stephan R. Hall Jonathan P. How, and James D. Paduano.

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 P. Belobaba, John-Paul B. Clarke, Erik Feron, and Amedeo Odoni. R. John Hansman directs ICAT. *Visit ICAT 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. It began in 1939 as the Servomechanisms Laboratory, an offshoot of the Department of Electrical Engineering. Its early work, during World War II, focused on gunfire and guided missile control, radar, and flight trainer technology. Over the years, the scope of its research broadened.

Today, LIDS' fundamental research goal is to advance the field of systems, communications and control. In doing this, it recognizes the interdependence of these fields and the fundamental role that computation plays in this research. LIDS conducts basic 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. Its staff includes faculty members, full-time research scientists, postdoctoral fellows, graduate research assistants, and support personnel. Every year several research scientists from various parts of the world visit the Laboratory to participate in its research program.

Currently, 17 faculty members, 20 research staff members, and approximately 110 graduate students are associated with LIDS. Aero-Astro LIDS faculty are John J. Dyest, Eric Feron, Wesley L. Harris, Daniel E. Hastings, Eytan H. Modiano, and Moe Win. LIDS is directed by Vincent W.S. Chan. *Visit LIDS at http://lids.mit.edu/*

LEAN AEROSPACE INITIATIVE

Read the detailed article on LEAN beginning on page 23.

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 sponsor 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 A. Hoffman Dava J. Newman, and Laurence R. Young, and the director, Charles M. 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 MVL at http://mvl.mit.edu/*

SOFTWARE/SYSTEM ENGINEERING RESEARCH LAB

Research in the Software/System Engineering Research Lab focuses on topics related to the design of complex systems having software components. The development of software in these systems cannot be separated from system engineering activities and much of the research in the lab would more properly fit into the category of systems engineering than software engineering. SERL research is cross disciplinary and spans aeronautics and astronautics, computer science, human factors and cognitive engineering, system safety engineering, and other disciplines and applications using computers for control (such as transportation and medical devices). Current research topics covered include system and software safety, software and system requirements, human-computer interaction, model-based system engineering, software sustainment, software productivity, diagnosis (health management), and real-time operating system kernels. SERL faculty include Charles P. Coleman, Nancy G. Leveson, and I. Kristina Lundqvist. *Visit SERL at http://sunnyday.mit.edu/serl.html*

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 lab is electric propulsion (see the article beginning on page 15), in which the electrical, rather than chemical energy propels spacecraft. The benefits are numerous and very 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 pacecraft-thruster interaction. Manuel Martinez-Sanchez advises the SPL research group. *Visit SPL at http://web.mit.edu/dept/aeroastro/www/labs/SPL/home.htm*

SPACE SYSTEMS LABORATORY

The Space Systems Laboratory engages in cutting-edge research projects with the goal of directly contributing to the current and future exploration and development of space. SSL's mission is to explore innovative concepts for the integration of future space systems and to train a generation of researchers and engineers conversant in this field. Specific tasks include developing the technology and systems analysis associated with small spacecraft, precision optical systems, and International Space Station technology research and development. The laboratory encompasses expertise in structural dynamics, control, thermal, space power, propulsion, microelectromechanical systems, software development and systems. Major activities in this laboratory are the development of small spacecraft thruster systems (see the Space Propulsion Laboratory) and researching issues associated with the distribution of function among satellites. In addition, technology is being developed for spaceflight validation in support of a new class of space-based telescopes that exploit the physics of interferometry to achieve dramatic breakthroughs in angular resolution.

SSL faculty and research staff include Oliver L. de Weck, Jonathan P. How, John E. Keesee, Manuel Martinez-Sanchez, David W. Miller, Raymond Sedwick, and Brian C. Williams. *Visit SSL at http://ssl.mit.edu/index.html*

MATERIALS AND STRUCTURES

The Materials and Structures Division has recently 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 and research staff include Paul A. Lagace, Raul A. Radovitzky, S. Mark Spearing, and Brian Wardle

WRIGHT BROTHERS WIND TUNNEL

Since its opening in September 1938, The Wright Brothers Wind Tunnel has played a major role in the development of aerospace, civil engineering and architectural systems. In recent years, faculty research interests generated long-range studies of unsteady airfoil flow fields, jet engine inlet-vortex behavior, aeroelastic tests of unducted propeller fans, and panel methods for tunnel wall interaction effects. Industrial testing has ranged over auxiliary propulsion burner units, helicopter antenna pods, and in-flight trailing cables, as well as new concepts for roofing attachments, a variety of stationary and vehicle mounted ground antenna configurations, the aeroelastic dynamics of airport control tower configurations for the Federal Aviation Authority, and the less anticipated live tests in Olympic ski gear, astronauts' space suits for tare evaluations related to underwater simulations of weightless space activity, racing bicycles, subway station entrances, and Olympic rowing shells for oarlock system drag comparisons.

In more than a half century of operations, Wright Brothers Wind Tunnel work has been recorded in several hundred theses and more than one thousand technical reports. Faculty and staff include Mark Drela and Richard Perdichizzi. *Visit the Wright Brothers Wind Tunnel at http://web.mit.edu/aeroastro/www/labs/WBWT/wbwt.html*

Leaving a legacy
EDWARD F. CRAWLEY

After seven years as head of the Aeronautics and Astronautics Department, Ed Crawley stepped down this past June. During his tenure as head, he was often asked why he expends so much time and energy on his cause célèbre, bringing reform to engineering education. His response is to grin and reply, "It's for the good of the children." Certainly and obviously, Ed doesn't see engineering students as children, it is the philosophy behind the old statement that is so important to him — he does it because he deeply believes it is the right thing to do.

Ed's unfailing desire to do things because they are the right thing to do is only one of the many traits that made him a wonderful leader of this department. He is a brilliant engineer. He is a successful entrepreneur. He is a dedicated educator. He is a tireless advocate for his department and his institute. These traits, when blended with the infectious nature of his boundless enthusiasm, have resulted in a tremendous increase to this department's physical as well as human resources. Under his leadership we repositioned our department, adding thrusts in aerospace information engineering and complex systems engineering to our historical strength of aerospace vehicle engineering. He raised more than $8 million to rebuild our home, the Guggenheim Aeronautical Laboratory, as the groundbreaking (and prizewinning) Learning Laboratory for Complex Systems. It was Ed who enticed more than 20 of the brightest aerospace researcher-educators from around the world to join the Aero-Astro faculty, broadly increasing our abilities and, equally important, our faculty's ethnic and gender diversity. And, it is Ed's ongoing development and leadership of the CDIO Initiative — the innovative engineering educational framework, born in the Aero-Astro Department, stressing fundamentals and set in the context of Conceiving—Designing—Implementing—Operating systems and products—that is inspiring universities throughout the world.

Ed is certainly not disappearing. He is already well along with his next challenge as executive director of the Cambridge-MIT Institute. And, of course, he will continue teach here in the department.

Perhaps unsurprisingly, Ed's tenure as head of this department was itself an exercise in CDIO. We began by Conceiving a new mission and strategy. The faculty, staff and students (teamwork being a major element of the CDIO pedagogy and philosophy) then Designed our educational goals, our curriculum, our teaching methods and our facilities. As the new millennium approached, we began Implementing this plan. And, now although Ed has stepped down, we Operate a vibrant, revitalized department that is well positioned to contribute to the future of aerospace. That's quite a legacy.