

AEROASTRO



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AeroAstro is published annually by the Massachusetts Institute of Technology Department of Aeronautics and Astronautics, 33-240, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA. <http://www.mit.aero>

AeroAstro No. 9, July 2012

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Cover: Alumni astronauts (from left) Mike Fincke (AeroAstro, BSc '89), Cady Coleman (ChemE, BSc '83), and Greg Chamitoff (AeroAstro, PhD '82), wearing MIT 150 anniversary t-shirts, send video greetings from the International Space Station to high school students around the world participating in AeroAstro's 2011 Zero Robotics competition. Each is accompanied by a Space System's Lab SPHERE microsatellite. For more on Zero Robotics and SPHERES, turn to page 25 (Video grab via NASA).



THESE ARE EXCITING TIMES FOR AEROASTRO.

Our research funding has risen by 40 percent over the past three years: there are more than 170 research projects in our labs and centers representing \$28 million in expenditures by the Department of Defense, NASA, other federal agencies and departments, and the aerospace industry. Our incoming sophomore class size is up by 48 percent over last year. Our faculty now includes a former secretary to the Air Force, a former astronaut, a former NASA associate administrator, a former USAF chief scientist, nine National Academy of Engineering members, nine American Institute of Aeronautics and Astronautics Fellows, two Guggenheim Medal recipients, and two AIAA Reed Aeronautics Award recipients.

This spring, we held a faculty retreat at which we began exploring potential new or expanded initiatives, directions and activities. Areas of focus were autonomous aerospace systems, data to decisions in aerospace systems (models and algorithms to interpret and understand large data sets and support the decision-making process), energy, and outreach.

Outreach is an area of growing importance both in AeroAstro and around the School of Engineering. If we are to ensure a strong field of competent future engineering leaders, we need to be exciting young people about engineering careers — especially, in our case, aerospace engineers. One of the first steps taken in this area is the MIT+K12 initiative, started by Engineering Dean/AeroAstro Professor Ian Waitz as a means to teach young students basic concepts in engineering and science. MIT students produce the videos, and AeroAstro's own have leapt to the challenge creating a number of interesting and fun video lessons. As an example, take a look at "Forces on an Airplane," <http://k12videos.mit.edu/content/forces-on-an-airplane>.

A terrific example of a unique and effective outreach program is AeroAstro's Zero Robotics challenge. Under the guidance of faculty and staff from our Space Systems Lab, high school students from throughout the United States and the world write programs for our SPHERES microsatellites. Those that make it to the finals watch a real-time downlink as their programs are executed using SPHERES aboard the International Space Station. More about Zero Robotics on page 25.



Indeed, we have a number of great projects and initiatives ramping up. One you'll be hearing much more about in coming months is renovating the department's facilities. Still in its early stages, this initiative includes creation of a sizeable state-of-the-art autonomous aerospace systems laboratory to be shared by our growing number of related research projects, and institution of a student avionics lab. We're also looking at a major renovation of the iconic, and still very much used, Wright Brothers Wind Tunnel. This is projected to include replacing the motor, fan, and electrics, most of which date to the 1938 opening; new instrumentation; cooling; and sound reduction. See the article on page 45 for more details.

In our introduction to the last issue of AeroAstro, we told you how excited and honored we were to be the then new AeroAstro department leaders, the latest in a distinguished line of individuals with unwavering commitment to educational excellence and advancing aerospace research. We couldn't have picked up the leadership mantle at a more rewarding time — the articles in this issue offer just a glimpse of the unparalleled work our world-class faculty, students, and staff are doing in research, education, and outreach. As always, we hope you will share with us your thoughts, ideas, and comments. Let's hear from you.

JAIME PERAIRE, Department Head

KAREN WILLCOX, Associate Head

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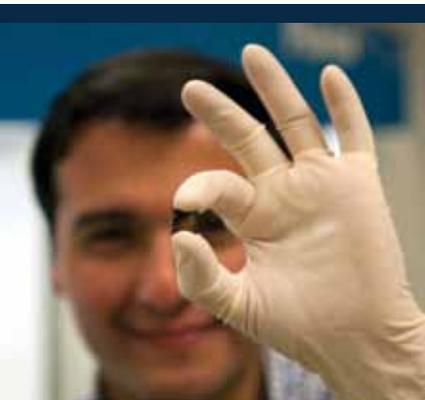
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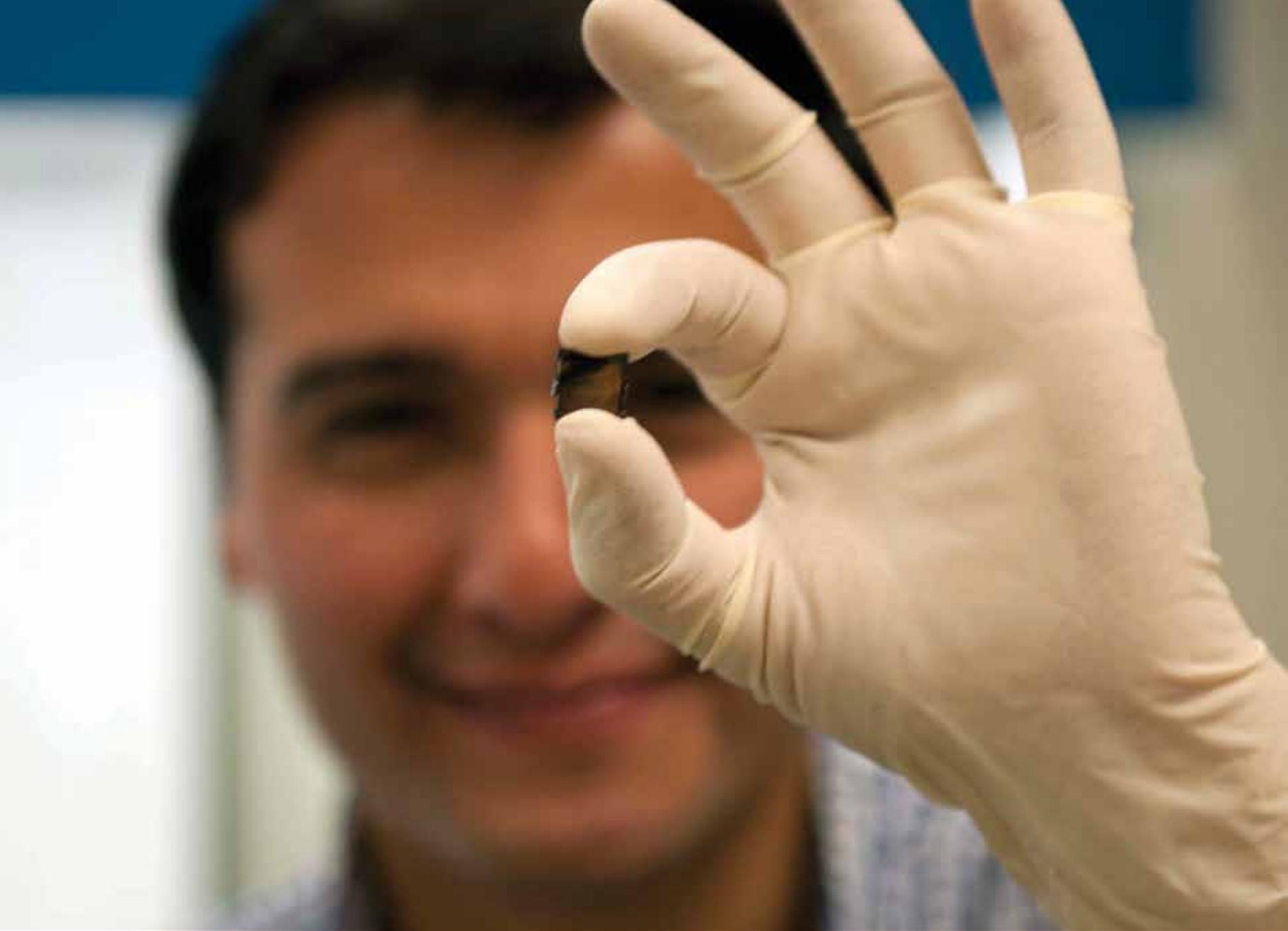
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The Space Propulsion Lab's penny-size electro spray thrusters comprise 500 microfabricated ion sources.

Tiny satellites getting very big in space engineering

By Paulo Lozano

At this writing, NASA has effectively cancelled two of its flagship missions to Mars. These were planned as ambitious, multinational collaborations.

Their goal was to study a number of key scientific issues, including the search for evidence of life in the Red

Planet's long history. These missions were cancelled because they were deemed too expensive, and their inclusion in the tight agency budget would force the cancellation of a number of other programs. This is but one example of the now pervasive incompatibility between lower budgets and challenging missions. Are we destined for a future with infrequent launches and fewer discoveries?

Scientists and engineers are not willing to let this happen: we want to be challenged and we continue to think about the next big discovery in our cosmic backyard. We want to look at ways in which the budget-vs.-challenge incompatibility is dissolved. Some of us are proposing a bold approach: instead of fewer missions, plan more.

FROM BEEPS TO BIOLOGY

About 10 years ago, the nanosatellite movement emerged as a way to engage students in space systems engineering. Nanosatellites are very small vehicles. A CubeSat, with a mass of only 1 kg and measuring 10 cm on each side, about the size of a Rubik's Cube, is an example of a now popular nanosatellite configuration. CubeSats are small and inexpensive, thus they have become ideal platforms for educators to teach subsystem integration. Back then, few people thought that such small form factors could ever do something useful if launched into space. Eventually, nanosatellites found their way into orbit and, over time, performed increasingly complex tasks: progressing from the first CubeSats' Sputnik-like beeps, to recent mission studies of space effects on biological specimens.

We could say that nanosatellites are coming of age as they get ready for a bright future driven by the phenomenal advances in the miniaturization of space technologies. Today, it is possible to package in such small vehicles sophisticated power, attitude determination, communications, thermal, and payload subsystems. I realize this in real-time as I write this article on my tablet computer, which is somewhat smaller and lighter than a nanosatellite and has pretty much the same systems onboard.

THE PROPULSION PROBLEM

Still, there is one subsystem that has proven to be particularly tricky to miniaturize: a way to move the satellite around in space. For many missions, propulsion is not required, and nanosatellites have so far thrived without it. However, propulsion in nanosatellites would provide

a significant kick in overall capability. It would enable a whole new class of space missions for such small gadgets. It would allow us to think big.

Ideally, one would like scaled-down thrusters to occupy a small fraction of the satellite's mass and volume, efficient in power and propellant used, and affordable to the nanosatellite developer.

The field of micropropulsion development for small spacecraft is active and growing. Many different concepts have been proposed, with some of them reaching the maturity level required for tests in space. There are a number of physical and manufacturing limitations that make the miniaturization of propulsion systems both

challenging and exciting. Taking an existing propulsion system and shrinking all of its components down in proportion to fit in a nanosatellite sounds like an elegant solution. However, in most cases this is not possible without serious hits on system performance. In chemical propulsion systems like your traditional "rocket engine," propellant storage, flow control and usage take the greatest toll. The amount of propellant required for a given mission can be dramatically reduced with plasma (electrically charged gas) thrusters. But, most electric propulsion engines must remain disproportionately large with respect to the host spacecraft as they are scaled down. More challenging still, as they grow smaller, electric engines become less efficient, transforming little of the limited electrical power available into useful force.

Ideally, one would like scaled-down thrusters to occupy a small fraction of the satellite's mass and volume, efficient in power and propellant used, and affordable to the nanosatellite developer. In AeroAstro's Space Propulsion Laboratory, we have been working on a thruster concept with these characteristics. We call it iEPS, which stands for ion Electrospray Propulsion System. iEPS is a great candidate for nanosatellite propulsion because it combines high performance and compactness. Three words and one acronym summarize why this is possible: propellants, field, flow, and MEMS.

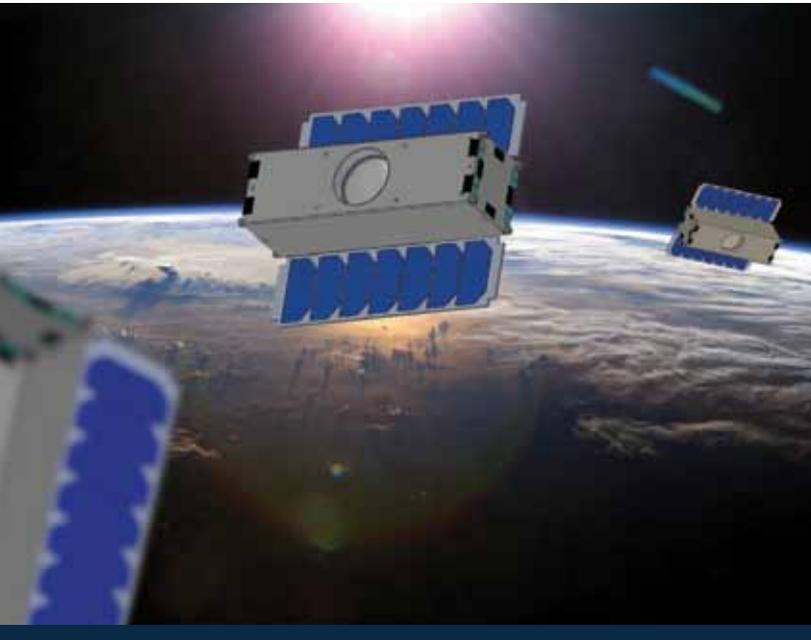
The propellants are zero-vapor pressure, room-temperature molten salts, also known as ionic liquids. These amazing substances can be exposed to the vacuum of space with practically no evaporation. As such, they can be stored without pressurization directly in the dense liquid phase. There is no need for pressurized reservoirs, thus removing complexity and system mass.

Since these salts are composed exclusively of positive and negative ions, there is no need for a large chamber in which gaseous propellant is electrically charged, like in regular plasma thrusters. This eliminates most of the engine volume and energy losses. Instead, we make use of an electric field applied to the liquid/vacuum interface that overcomes surface tension. The applied field deforms the free surface into a conical structure with a fine tip that amplifies the electric field to values of about one billion volts per meter. Under such strong fields, ions cannot remain in the liquid phase and are effectively evaporated and accelerated to very high velocities, producing thrust.

For this concept to work, the propellant has to flow easily from the reservoir to the field emission site. Instead of using a pump, we take advantage of bulk porous structures so the liquid moves freely through capillary forces alone. In addition, the pore size is so small that there is no need for isolation valves to control flow delivery. The only actuator is the voltage that generates the field. The absence of pumps, valves and pipes allow for potentially tiny designs.



Paulo Lozano works with a magnetically levitated spinning CubeSat — a vehicle that could be maneuvered by miniature propulsion systems — in a prototype balance that simulates the thrusters' zero-g characteristics.



Development of CubeSats, miniature satellites with a volume of one liter, makes it possible to design and produce satellites at low cost. (Rebecca Jensen-Clem/MIT graphic)

MEMS THE WORD

Finally, much of the thruster promise could only be realized through advanced manufacturing. We make use of MEMS (micro-electro-mechanical systems) techniques to fabricate a small silicon package that contains all thruster elements. In particular, the force produced by a single ion-emitting site is too small even for a nanosatellite, so we have to microfabricate hundreds, or thousands, of individual porous emitters, sharp enough to minimize operating voltages. Silicon is not the best material for the emitters, so we need to use monolithic integration of materials with dissimilar properties. In our current design we integrate silicon with porous metals with features formed via electrochemical micro-etching. The tolerances required for these devices are way too small for traditional machine-shop tools, for this reason we need to use, and sometimes develop, our own photolithographic-based processes.

iEPS thrusters are about 1×1 cm and 2.5 mm thick, and contain 500 emitter tips. Depending on the applied voltage, each generates from one to ten high velocity ion beams. It is designed to provide thrust to a CubeSat using electrical power from its solar cells, or about 2 W. If more power was available, instead of a larger thruster, we would simply increase the number of emitters and keep the thruster area constant.

Due to power limitations, these engines produce little thrust, just about the weight of $1/400$ of a letter-sized sheet of paper. However, once in space, over time even a small force like this produces significant mobility. For example, these thrusters could provide a way to point the spacecraft in

a given direction and very precisely aim for a long time towards, say, a group of stars looking for signs of exo-solar planets. It could also be used to control the relative position of a group of small satellites, counteract tenuous atmospheric drag in low orbits or force the reentry at the satellite's end of life to prevent the accumulation of more space debris. All these maneuvers will require small amounts of propellant — from milligrams to a few grams at most — since the iEPS uses it much more efficiently than standard chemical thrusters.

As the thruster is tested and improved, we are preparing it for launch. The first missions will be to qualify the technology and understand better its behavior in space. What is perhaps most exciting is what lies ahead. If you are able to integrate in a nanosatellite a compact and efficient high specific impulse thruster, then you could think about challenging, bold missions. These very small vehicles could use onboard propulsion to steer them away from the earth's gravitational well and into deep space, or spiral up and reach the moon, asteroids and planets, carrying small but efficient research payloads. Nanosatellites equipped with these thrusters would cost a fraction of today's large missions. This is where budget meets challenge, and challenge can win big. So, if you are interested in being a space explorer, turns out it is perfectly possible. Nanosatellites could bring space closer to the ground. These are budget-constrained times — difficult times in some sense — but are also times of opportunity that can be harnessed through the development of technologies that enable the solution to difficult problems. As always, the ingredients here are passion, creativity, innovation, and a sense of adventure. ➔

If you are able to integrate in a nanosatellite a compact and efficient high specific impulse thruster, then you could think about challenging, bold missions.

PAULO LOZANO is an associate professor of Aeronautics and Astronautics. His interests are in electric propulsion, electrosprays, thruster physics, electrochemical microfabrication, engine health monitoring, space mission design, small satellites, focused ion beams, and nanofabrication. He may be reached at plozano@mit.edu.

In the Interactive Robotics Group Lab, doctoral candidate Stefanos Nikolaidis uses a virtual environment to research human-robot interactive training. Nikolaidis controls the white anthropomorphic robot while the orange industrial robot learns a task plan to safely assist.



Revolutionizing manufacturing via human-robotic partners

By Julie Shah

If you walk through an automotive assembly plant, you'll see many large, fast-moving robots helping with the work. But they will be working in cages far away from the human mechanics.

Generally, industrial robots are dangerous and must be kept physically separate from people. Robots do some tasks while people

do others, and there is very little interaction. As a result, assigning tasks to humans or robots has traditionally been seen as an either/or proposition.

In MIT AeroAstro's Interactive Robotics Group, we think, why not both? Harness the strengths of people and robots working together and reimagine assembly plants of the near future. We can remove the cages around manufacturing robots and use the state of the art in human-robot teaming to do the job better, more productively, and more ergonomically than was previously possible.

TASKS IN ISOLATION

Traditionally, the success of industrial robotics has been predicated on the design of highly structured, repeatable tasks that are performed in isolation. In the automotive industry, the result is a split factory; one side, robots; the other side people. The impact of this imposed dichotomy is even more pronounced in the aerospace manufacturing industry. Large commercial airplane assembly has been primarily manual work. Tight integration and variability in the build process made it difficult to physically isolate elements for robotic-only work without significant detriment to efficiency and workflow.

We're at the beginning of a new era in the use of industrial robots. Recent advances in computation, sensing, and hardware enable robotics to perform an increasing percentage of traditionally manual tasks. Yet, the assembly mechanic cannot be removed entirely from the process. This provides new economic motivation to explore opportunities where assembly mechanics and industrial robots may work in close physical collaboration. In recognition of this growing need, within the past year the International Standards Organization has begun the process of defining standards and safety requirements for collaborative industrial robots—large, potentially dangerous industrial robots working and coordinating in the same space as people.

While we're seeing progress in robot safety standards, significant leaps in adaptive planning and control technology are needed if we are to successfully integrate industrial robots into human workflow. Our MIT Interactive Robotics Group is developing technology to enable collaboration with industrial robots on two levels: one-to-one human robot teamwork, and

While we're seeing progress in robot safety standards, significant leaps in adaptive planning and control technology are needed to integrate industrial robots into human workflow.

factory-level sequencing and scheduling of human and robotic tasks. Our goal is to open the door to a new class of manufacturing processes that achieve significant economic and ergonomic benefit through robotic assistance in traditionally manual processes.

Ultimately, throughput improvements will be achieved through parallelization of work and reassignment of non-value added tasks. Human-robot interaction will be designed to eliminate human workers' fatigue and repetitive stress. Our approaches to designing and analyzing human-robot collaborative systems also have application to other safety-critical domains, such as cancer surgery and astronaut-robot co-work in space.

ROBOTIC ASSISTANCE IN COMPLEX, MANUAL TASKS

Industrial robots are being introduced to work as robotic assistants to mechanics performing manual assembly tasks. Robotic assistants provide productivity benefit by staging tools and parts for the mechanic. Robots can also manipulate, rotate, and translate parts and assemblies, alleviating mechanics' repetitive stress and fatigue.

Safety is one critical consideration when introducing industrial robots to work alongside people on the assembly line. Real-time adaptive control is required to limit robot velocity and acceleration as a function of human proximity, motion, and situational awareness. For example, as the human moves closer to the robot, the robot should slow down. If the person looks away, the robot should stop moving. The adaptive control must be risk sensitive and responsive to uncertainty in sensing of the human's location and movements. As with human safety-critical operations, safety within the human-robot team is inextricably tied to understanding team members' intent, situational awareness, and predictability of team members' (human and robot) behavior.

Safety isn't the only challenge. Programming a robot to work in a team with a person isn't possible with currently available industrial robot interfaces. Mechanisms exist to program multiple robots' coordinated movements, but these require repeatable motions with preprogrammed synchronization points. These techniques aren't applicable to programming human-robot teamwork. Many manual processes are more art than science, and workflow changes significantly from worker to worker, shift to shift, based on personal preferences and technique. Substantial difficulties arise in attempting to capture convergent team behavior using traditional programming scripts.

The Interactive Robotics Group is developing new adaptive control methods that couple safety mechanisms with high-level, person-specific planning and execution mechanisms to promote



Professor Julie Shah observes while grad students Ron Wilcox (left), and Matthew Gombolay coordinate human-robotic interaction. Gombolay is driving fasteners through a sealant that the robot has applied. Timing is critical; the sealant dries rapidly, so the fasteners must be placed within a few seconds of sealant application. If the robot and human are to work safely and productively with each other, the robot must continually sense the human's performance, adapting its timing to the person's.



Robots, like these fast-moving machines in an auto plant, work behind protective cages — they're just too dangerous to be in proximity to humans. AeroAstro's Interactive Robotics Group is developing ways to make robots sensitive to their human coworkers, enabling productive robotic-human proximity and partnerships. (Shutterstock)

predictable, convergent team behavior. This includes statistical methods for characterizing the predictability of the human-robot team and driving robot control. We apply human factors modeling coupled with statistical methods for planning and control to derive quantitative methods for assessing the quality and convergence of learnt teaming models, and to perform risk-sensitive, real-time robot control on the production line. The expectation is that these methods will yield quantitative improvements in human-robot team safety and performance.

HUMAN AND ROBOTIC COORDINATION

We're also developing computationally efficient methods for coordinating human and robotic sequencing and scheduling at the factory-level. Tight integration of human workers and robotic resources involves complex dependencies. Even relatively small increases in process time variability lead to schedule inefficiencies and performance degradation.

To harness these new interactive robotic systems' efficiency, we're creating decision-making and control techniques to adaptively coordinate the work sharing and scheduling among multiple robots and people. Re-computations of robot tasking and scheduling must be calculated very quickly, to be responsive to people working and coordinating in the space physical space. The computational methods must also provide real-time guarantees that schedule deadlines and other operational constraints will be met. Our methods allow fast computation of robot schedules in response to inevitable disturbances due to robot servicing and other variable delays in the build process.

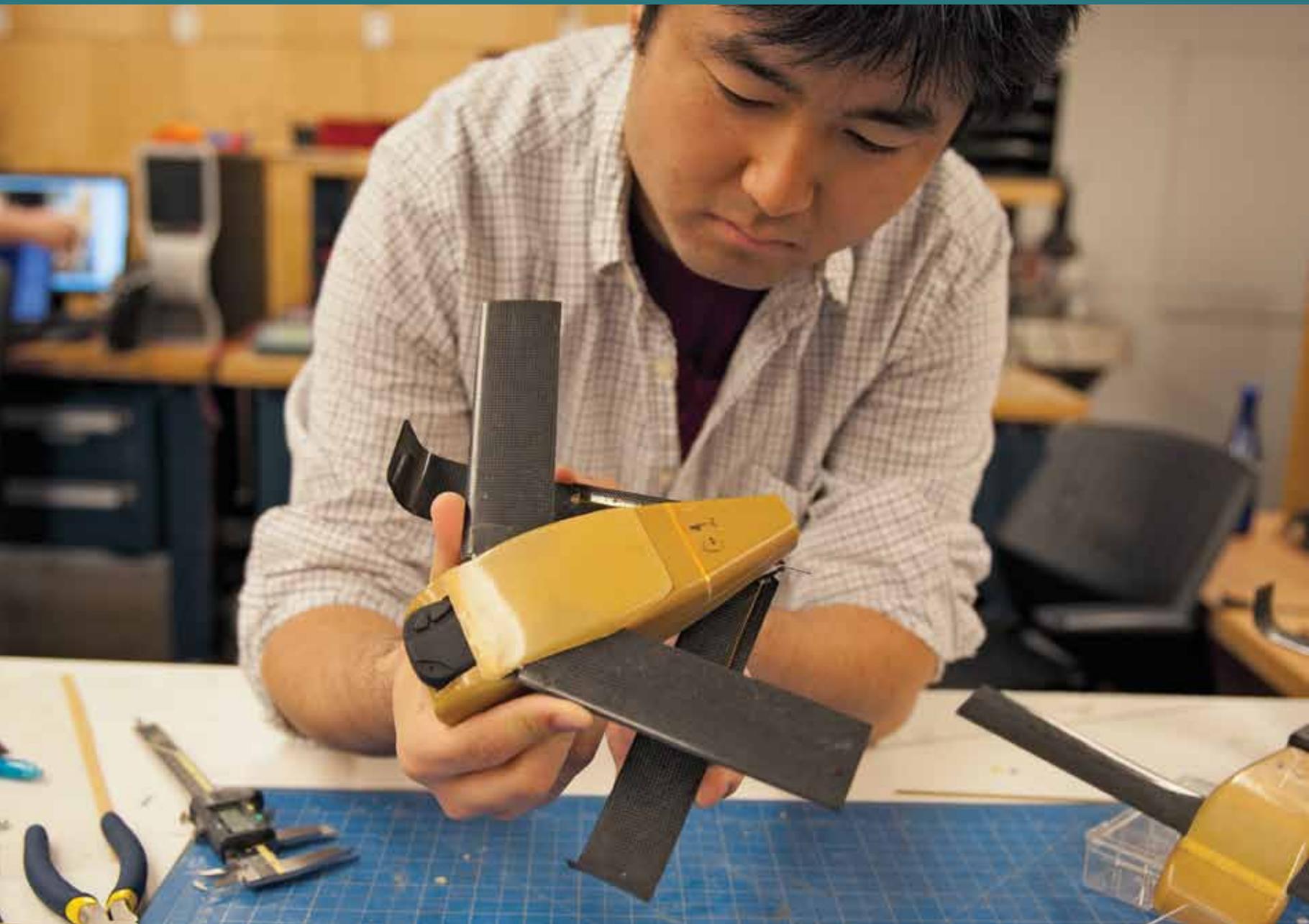
Another area of interest is capability for a single operator to direct a team of robots. Our methods support a supervisor ability to specify, for example, that a set of jobs be delayed by a certain amount of time to provide a safe working environment for the quality inspection team. Work will be shifted according to operator preferences through fast recomputation of the robots' schedule, while preserving guarantees that assembly will finish within specified deadlines. These types of user control interfaces are designed into the coordination algorithms to provide for both the usability and capability of interactive industrial robots within a unified framework.

This research will open new opportunities for robotics in manufacturing. We envision a future where dynamic coordination of human-robotic work enables greater assembly and manufacturing efficiency, with robotic assistance in manual tasks improving ergonomics and increasing their human partners' productivity. →

We envision a future where dynamic coordination of human-robotic work enables greater assembly and manufacturing efficiency.

JULIE SHAH is an assistant professor in the MIT Aeronautics and Astronautics Department. She leads the Interactive Robotics Group in the Computer Science and Artificial Intelligence Laboratory, and is faculty in the Man Vehicle Laboratory. Her research interests are autonomous systems, human-robot collaboration, AI planning and scheduling, and interactive robotics for aerospace, manufacturing, and medical applications. Julie Shah may be reached at julie_a_shah@csail.mit.edu.

Master's candidate Tony Tao folds the wings of a Locust, a micro UAV developed by AeroAstro students working with Lincoln Laboratory and Aurora Flight Sciences. The vehicle was fabricated using equipment in AeroAstro's Gelb Lab and tested in the department's Wright Brothers Wind Tunnel.



SKUNKWORKS, PHANTOMWORKS: WATCH OUT FOR BEAVERWORKS!

AeroAstro students design, build novel vehicles for real-world customers

By R. John Hansman

Lockheed has its Skunkworks, Boeing has its Phantomworks, and now MIT has the Beaverworks where students are designing, building, and testing novel unmanned air vehicle concepts in Building 33's Gelb Lab.

The Beaverworks concept, named after MIT's mascot, the beaver, originated when one of the Lincoln Laboratory directors approached the AeroAstro department about ways to increase the interaction and collaboration among the MIT Main Campus, Lincoln

Laboratory, and the U.S. Air Force. The idea was to commission the students in the aircraft systems design classes to design, build, test, and deliver actual flight vehicles, which would be used to support Air Force testing.

Now in its third year, Beaverworks has designed and delivered two successful vehicles. This has proven a unique opportunity for the students to integrate their academic experience with real world engineering experience.

UAV FOR CALIBRATION OF GROUND BASED SENSOR SYSTEMS

The design problem in 2009, Beaverwork's first year, was to develop a vehicle to fly calibrate the antenna patterns of ground based sensor systems. A Falcon jet test aircraft is currently used for this mission. The UAV needed to be capable of carrying a sensor payload including a 1-meter long antenna up to 25,000 ft for one to three hours. Minimizing the use of metal was important to avoid interfering with the antenna pattern. The vehicle had to be transportable (i.e., fit within FedEx shipping constraints) and be launchable and recoverable from remote test locations.



Beaverworks team members (from left) master's candidate and student lead Tony Tao, and undergrads Blake Chambers, Sam Range, Jon Allen, Rebecca Colby, with various incarnations of the micro UAV. The larger aircraft is double-sized prototype they built to equip with an off-the-shelf autopilot while the miniature autopilot was in fabrication.

To meet this challenge, the undergraduate and graduate aircraft design classes were integrated and expanded to two semesters, increasing the skill and size of the design build team. The integration had the collateral benefit of allowing cross learning between the graduate and undergraduate students. The students were given the initial requirements, but were expected to interact with the Lincoln and Air Force “customers” to clarify requirements and mission needs. The students were given a \$50,000 budget and a deadline of the end of the Spring semester.

The fall semester was focused on design. The students were initially grouped into small concept design teams to allow each student to play a strong role in the conceptual design. The initial

concepts were presented to Lincoln and Air Force representatives in a Concept Design Review. Based on the feedback, several of the best features of the initial concepts were selected and the students were reformed into disciplinary teams to support preliminary design. By the critical design review at the end of the fall semester the students had completed the airframe design, launcher system, and avionics system architecture.

Construction of the first prototype vehicle was started during the January 2010 Independent Activities Period, MIT's annual four-week opportunity for its community to organize, sponsor and participate in a variety of activities, including how-to sessions, forums, athletic endeavors, lecture series, films, tours, recitals and contests. The students used this prototype to test and develop manufacturing techniques for the Kevlar honeycomb fuselage and the foam core fiberglass wing and tail construction. The prototype was used for multiple tests including radio controlled flight tests and antenna interference measurements, conducted in the Lincoln anechoic chambers. Many lessons were learned and modifications were made to the design including increase fuselage size, improved landing gear, and modified tail sizing and antenna mounting.

During the spring semester, the students built the second flight vehicle, which included an autopilot capable of autonomous flight. This vehicle performed a full-scale demonstration of a simulated calibration antenna calibration mission in a test range near the former Otis Air Force Base on Cape Cod. To obtain approval for test range use, the students had to develop and present to the Air Force a detailed test plan, including a detailed safety and hazard analysis.

As their final report, the students briefed their design and test results to a tough audience of more than 300 Air Force and industry professionals at the Air Vehicle Survivability Conference held at Lincoln Lab in May. One major aerospace company's senior VP noted that the students delivered a vehicle that met the key performance criteria within time and under budget on an extremely tight schedule.

One major aerospace company's senior VP noted that the students delivered a vehicle that met the key performance criteria within time and under budget on an extremely tight schedule.



Christopher Jarrette works on Beaverwork's 2009-2010 project, a UAV for the U.S. Air Force to use in calibrating ground based sensor systems' antenna patterns.

DEPLOYABLE MICRO UAV

The vehicle design problem for the second year increased the degree of difficulty. The requirement was to develop a small expendable UAV that could be deployed from a full-scale aircraft at 30,000 ft and autonomously fly a one-hour environmental monitoring mission. The preferred launch platform was a flare dispenser, which required the vehicle to fit into a 2 inch by 2.5 inch by 7 inch cartridge and be capable of tolerating 300g launch loads.

The course took a trajectory similar to its predecessor. In the first semester the students developed

and evaluated concepts for vehicle deployment and for testing key performance issues, such as battery capacity in the cold temperatures at high altitude. Because there were no autopilots small enough to fit the vehicle, working with Lincoln Laboratory and Aurora Flight Sciences, the students designed an autopilot board based on an Aurora design. Again, Lincoln Laboratory and Air Force reviewers participated in the design reviews, and a unique folding wing design was detailed by the end of the semester.

During Independent Activities Period, the students built foam and balsa wood glider models. They encountered lateral stability problems, which they fixed by modifying the rear wing design.

In the spring semester, the students built a double-size prototype of the aerodynamic configuration and flew it as a radio controlled model to confirm stability and handling qualities. This large-scale prototype allowed testing of autopilot control laws using an off-the-shelf autopilot while the miniature autopilot was in fabrication. The students then built molds, with which they constructed an actual scale prototype with a Kevlar fuselage and carbon wings. This was tested in AeroAstro's Wright Brothers Wind Tunnel, where they uncovered aerodynamic issues associated with manufacturing tolerances for the very thin wing (laminar separation bubble); a new wing was designed that resolved the issue and yielded a vehicle lift to drag ratio over 10. As a parallel

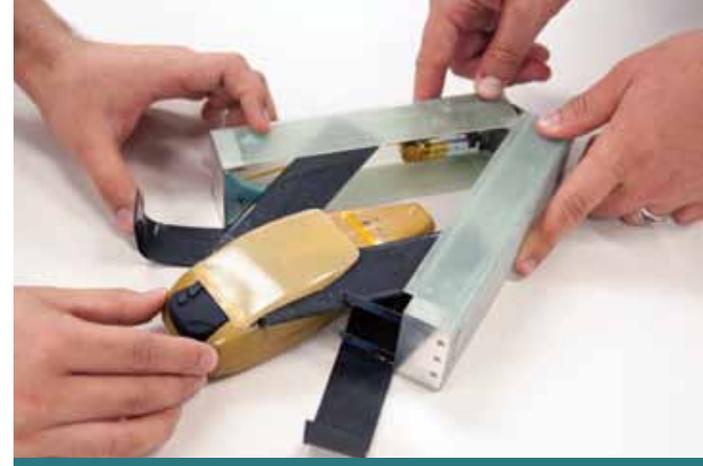
effort, a series of deployment prototypes were developed to refine the wings' mechanical deployment. At semester's end, the system and the results of the aerodynamic and deployment tests were again briefed by the students at the Air Vehicle Survivability Conference.

Over the summer, a student group continued work on the vehicle system as part of MIT's Undergraduate Research Opportunity Program. They refined the construction techniques, building fully deployable and flyable prototypes as well as a protective canister for the vehicle. These prototypes were fired from a Lincoln Laboratory launch system to test the ability to stand the 300 g launch loads. The students then conducted a full deployment test, dropping the canister from a balloon and demonstrating the vehicle's ability to recover under radio control.

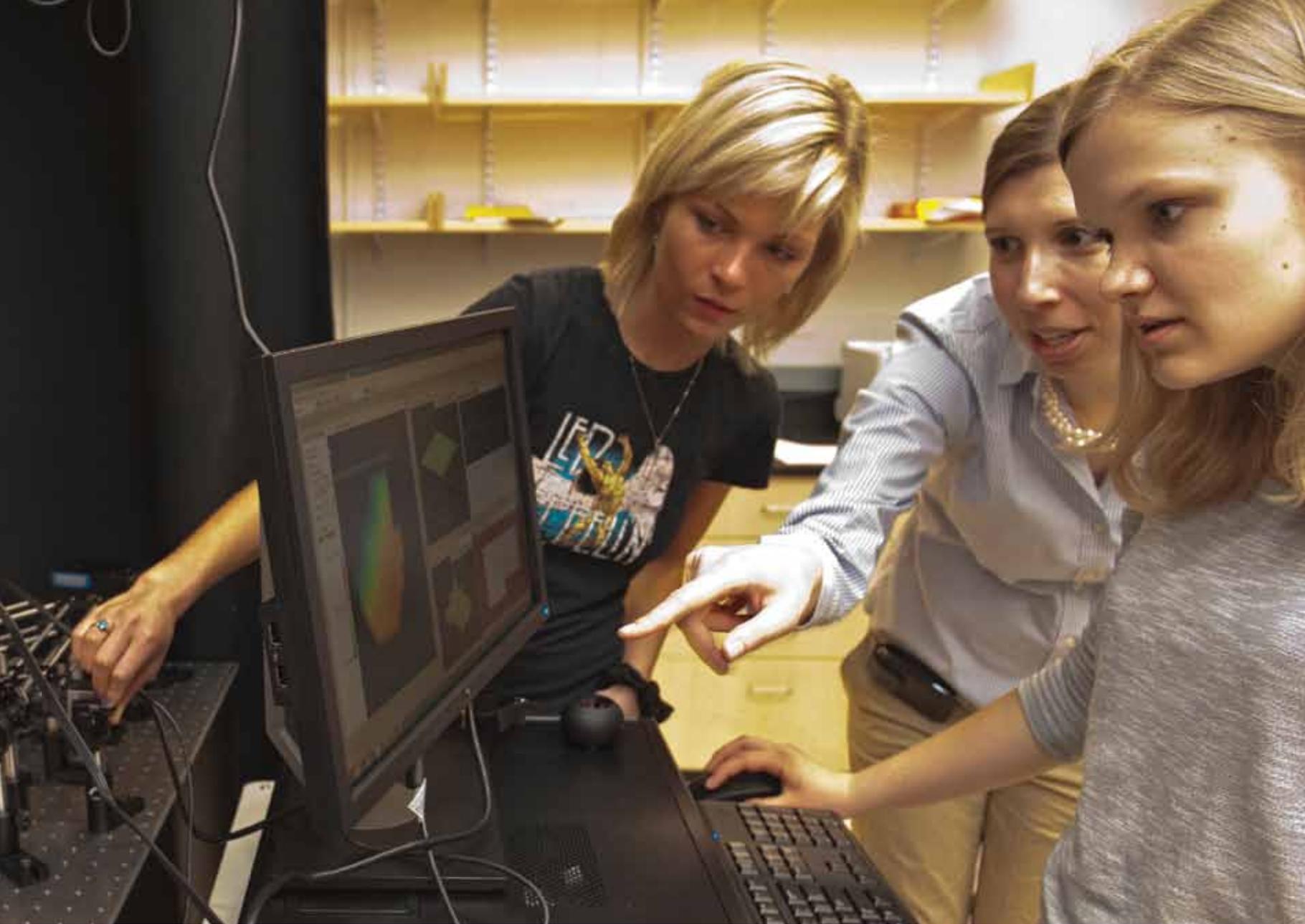
At this writing, the team is conducting autopilot system refinement and testing leading to vehicle ejection tests from the Lincoln Laboratory test aircraft.

Beaverworks is a tremendous opportunity for students to get hands on experience in a real system development and test. This has been a remarkable collaboration among AeroAstro, Lincoln Laboratory, and the Air Force. Both Beaverworks projects have led to continued development of the student concepts by Lincoln Laboratory and industry, which is a testament to the creativity, innovation and quality of the students work. New ideas for follow-on Beaverworks projects are under discussion. →

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



The Locust micro UAV is inserted into a plastic cartridge and then loaded in a military aircraft's flare dispenser. When ejected from the aircraft at altitude, the container opens, the Locust emerges, the wings unfold, a pusher prop (not fitted to this example) spins, and the aircraft begins its mission.



In the Wavefront Control Lab, grad student Ingrid Beerer (left) adjusts the Shack-Hartmann wavefront sensor (an optical instrument used to characterize an imaging system) while Professor Kerri Cahoy shows undergrad Caitlin Kerr how to handle calibration.

PLANETS, PLANETS, EVERYWHERE

Spacecraft wavefront control systems characterize Earth-like exoplanets

By Kerri Cahoy

Extrasolar planets, or “exoplanets,” are exotic planets that orbit around distant stars. Twenty years ago, the first tentative exoplanets detections were published: the question was were these objects really planets?

These initial detections have been methodically confirmed over the years by making observations that put constraints on the candidate planets’

mass. The difference between a star and a giant planet is that stars have enough mass to be “hydrogen-burning,” that is, they can fuse four protons to form a helium nucleus. There are sub-stellar objects called brown dwarfs that have enough mass (about 13 times the mass of Jupiter) to fuse deuterium, but not hydrogen. Planets are defined to be below this 13 Jupiter mass limit, planets are not massive enough to support thermonuclear fusion of deuterium.

The number of confirmed exoplanets — currently 760 — continues to grow. The number of yet-unconfirmed candidate exoplanets has leapt to more than 2,000, largely due to the rich harvest of observations from the Kepler dedicated space telescope mission. The confirmed exoplanets are all within the limits of our own Milky Way galaxy. To put this in perspective, the spiral Milky Way is about 100,000 light years across, the Earth is about 27,000 light years from its center, and the next closest galaxy is about 25,000 light years from Earth. The closest confirmed exoplanets are about 10 light years away from Earth.

ANOTHER EARTH?

Are there any Earth-like exoplanets? Could any exoplanets support life?

Answering these questions requires significant technological advances in spacecraft systems. Most current exoplanet observations are indirect, meaning that the presence of a planet is inferred by making observations of its parent star. The two primary indirect techniques are called the radial velocity and transit photometry methods. In radial velocity measurements, the rainbow-like spectrum of a target star is observed. The star has a large number of different absorption and emission features at different wavelengths. An exoplanet orbiting the star causes the pair to orbit their common center of mass. This motion results in a Doppler shift of the stellar spectrum, the lines shift to redder wavelengths as the star moves away and shift bluer as the star gets closer. For transit photometry, a telescope observes a star continuously and looks for the periodic decrease in brightness that occurs when a planet crosses in front of the star. For an Earth-sized planet, this decrease in brightness might be on the order of 1 in 10,000 according to the Kepler space telescope scientists. The radial velocity and transit photometry approaches for

A high performance version of a coronagraph can be used to block the parent star's light, but save the light from the nearby exoplanet.

detecting exoplanets are already successful (558 and 196 of the detected planets to date, respectively) and they can answer the question of whether or not a planet is the same size as Earth.

But to confidently answer the question of whether an exoplanet is Earth-like and could support life requires making observations of the planet's spectrum by itself and looking for absorption features that correspond to molecules containing the four elements most vital for life: oxygen, nitrogen, carbon,

and hydrogen. This can be done using a method called direct imaging where a telescope is used to image an exoplanet system. The light from the parent star is about 100 times brighter than the light reflecting from the star off of an Earth-like exoplanet and back to the observer. A high-performance version of a simple device called a coronagraph can be used to block just the parent star's light, but save the light from the nearby exoplanet.



Master's candidate Anne Marinan controls a liquid crystal spatial light modulator to form the letters "MIT."

While direct imaging measurements of bigger, brighter giant planets have already been made, such as those of the multi-planet system HR 8799, (29 light years away from Earth in the constellation of Pegasus), it is much easier to do this for a giant planet than it is for an Earth-like planet. For example, Jupiter is about 10 times the diameter and 300 times the mass of the Earth, which implies a much larger amount of both reflected light and thermal emission. There are still major technological advances that need to be made in order to make the same measurements of a smaller, dimmer Earth-like exoplanet.

THE WAVEFRONT CONTROL LAB

AeroAstro's Wavefront Control Laboratory addresses some of the key technological challenges in making direct imaging measurements of exoplanets by using tiny, low power, and lightweight microelectromechanical systems (MEMS) deformable mirrors and liquid crystal optical devices called spatial light modulators. Even with a high-performance coronagraph that is designed to achieve the 10¹⁰ contrast required, design and implementation are different matters. In reality, diffracted and scattered light from the other optical components in the system prevent the ideal contrast level from being reached unless there is active detection and correction of these contrast-wrecking "speckles."

There are still major technological advances to be made to make measurements of small Earth-like planets.

While there are adaptive optics systems that can correct for wavefront errors, there are unique aspects to the exoplanet direct imaging problem that require further development. Most importantly, the wavefront control systems need to function in space. This is because it is not feasible to take images from the ground that can both correct for wavefront distortions from atmospheric turbulence as well as achieve the necessary contrast to observe an Earth-like exoplanet. Therefore, these space wavefront control systems need to be small, low power, and lightweight.

The Wavefront Control Laboratory is demonstrating wavefront control with MEMS deformable mirrors, studying different configurations of mirrors to optimize control, and evaluating their environmental properties for use on space telescopes. The lab is using liquid crystal spatial light modulators to simulate wavefront errors and evaluating these modulators for use as the coronagraph itself.

In addition, these high-contrast exoplanet observations will generally be “photon-starved,” meaning that the spacecraft will need to maintain precise pointing control over a long period of time in order to collect enough photons to make a valid measurement. Coupling between the spacecraft attitude determination and control system, and the optical observation and wavefront control system will also be necessary. The instrumentation, control algorithms, and analysis tools being developed by our faculty and students will not only contribute to exoplanet imaging systems, but also have applications in aerospace optical communication and surveillance.

Of course, we don’t yet know the answers to questions, “Is there another Earth?” and “Are we alone?” In coming years, the Wavefront Control Laboratory will contribute the hardware and engineering pieces needed to help solve these puzzles. →

KERRI CAHOY is a Boeing Assistant Professor of Aeronautics and Astronautics and director of the Wavefront Control Lab. She may be reached at kcahoy@mit.edu.

Video game entrepreneur and commercial space use supporter Richard Garriott speaks to 2011 Zero Robotics finalists at MIT. On screen, the live downlink from the International Space Station will show the SPHERES microsattellites executing the competing programs.



Zero Robotics competition lets kids “touch space”

By Alvar Saenz-Otero, Jacob G Katz, and David W Miller

Many of us with a love for aerospace can testify that, as children, we dreamt about one day working in space. Through Zero Robotics, that day is today.

The U.S. Congress designated the International Space Station a National Laboratory in 2010, expanding its roles for society and enhancing the ability to use the ISS for educational objectives.

AeroAstro’s Space Systems Laboratory created Zero Robotics to enable middle and high school student participation in the science conducted aboard the ISS. The program uses the SPHERES microsattellites aboard the ISS. SHPERES are an MIT AeroAstro project that started in 1999 as part of the department’s Capstone Class, a class where students employ the conceive, design, implement, and operate skills they’ve learned in their time in AeroAstro. Zero Robotics specifically promotes interest in science, technology, engineering and mathematics, or, as it’s popularly known, STEM. The program is based on the successful history of the FIRST Robotics international high school robotics competition, where students build hardware robots controlled by humans. Zero Robotics is a complement to FIRST, since ZR opens development of SPHERES software algorithms that run autonomously.

NOT JUST A GAME

“Zero Robotics is not just a game, it’s a challenge to learn new things, to form teams, to find creative engineering solutions ... [to] encourage you [students] to follow your dreams,” astronaut Gregory Chamitoff, AeroAstro PhD ’92, said in introducing the program from aboard the International Space Station. Zero Robotics is a tournament that consists of four main stages: (1) run



Students test their Zero Robotics game simulations against other competitors via this online hi-fidelity online simulation. (Zero Robotics image)

tests in 2D simulation (online), (2) run tests in 3D simulation (also online), (3) create “alliances” of multiple teams who will all work together and, (4) run elimination rounds (online) to find the finalists that will see their code run aboard the ISS on SPHERES satellites.

The two main annual activities of Zero Robotics are:

- » High School Tournament—an open competition that runs from September through December where a national audience of high-school teams competes through several elimination rounds for the opportunity to reach the finals.
- » Middle School Summer Program—a five-week summer program designed to immerse middle students in programming and the math behind microgravity physics (dynamics of spacecraft). The middle school program requires substantially more involvement of the SPHERES team to help summer-school instructors teach programming. Therefore, this program is centered regionally on MIT and other selected locations that can provide the necessary support.

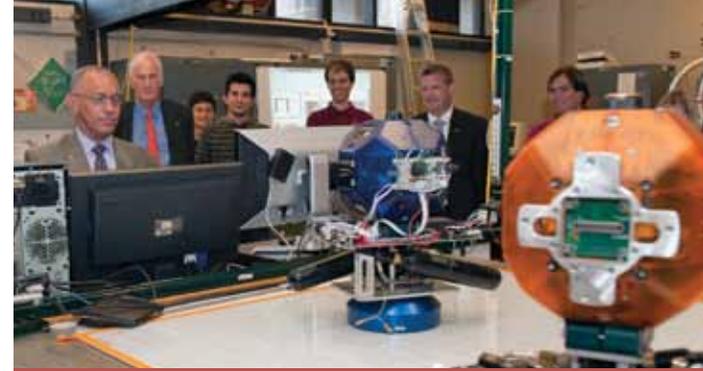
“To me, (Zero Robotics) is inspirational,” NASA Administrator Charles Bolden told a congressional committee. Inspiration is a key objective of Zero Robotics. By making the benefits, resources, and excitement of the space program tangible to the students, more young people may decide to become scientists and engineers. Zero Robotics seeks for students to take the concept of working for granted, allowing their imaginations to know no boundaries once they become science, engineering, and policy leaders. They will grow up pushing the limits of space exploration, engineering, and development. Of course, Zero Robotics also helps build critical engineering skills for students, such as problem solving, design thought process, operations training, team work, and presentation skills.

To date, there have been three high school tournaments and two middle school summer programs, each ending in a live round-robin final onboard the ISS. The 2011 high school competition saw the

participation of more than 140 high schools from throughout the United States and Europe. The success of the 2011 event, which involved more than 1500 students, suggests a promising future for the program.

The competition consists of the following major steps:

1. **Proposal submission:** teams submit a proposal, a process intended to teach students the basics of writing a proposal and organizing their team.
2. **2D simulation:** students implement all of the competitions tasks via simulation. This step verifies successful algorithm implementation prior to hardware testing, and allows for a baseline performance expectation.
3. **Ground demonstrations:** after reviewing their performance in simulation, teams with the best 2D simulation software see their code tested with the SPHERES ground hardware. The software for ground competition must account for computation and communications bandwidth limitations, as well as for the real disturbances such as friction, imperfect thrusters, and sensor noise. The ground demonstrations are conducted at MIT and webcast live to the schools.
4. **3D simulation:** all the teams compete in a full round robin of 3D simulation tests, where they expand their programs used in the 2D simulation round robin. The combined results of the 2D and 3D simulation tests are used to determine the semi-finalists who will compete to get their software to the ISS.



NASA administrator Charles F. Bolden Jr. (left) tries his hand at “flying” a pair of SPHERES microsatellites during a 2009 visit to AeroAstro’s Space Systems Lab.

SPHERES

The SPHERES program began in 1999 as the first AeroAstro CDIO Capstone Design Laboratory. A group of 13 MIT undergraduates designed two prototype satellites, which they flew aboard the NASA’s Reduced Gravity Aircraft in 2001. In 2003 the MIT Space Systems Laboratory and Payload Systems (now part of Aurora Flight Sciences) completed the flight units, which reached the International Space Station in 2006. The SPHERES facility consists of both ground and space hardware, with three satellites in each location. Each satellite has propulsion, wireless communication, and sensing sub-systems. The satellites can be reprogrammed to conduct different tasks. In this way, SPHERES has involved dozens of students in unprecedented levels of access to microgravity for experimentation and analysis at the undergraduate and graduate levels. To read more about SPHERES, see “Distributed Satellite Systems Offer Vision for Exploration and Education” in the 2004-2005 issue of AeroAstro <http://bit.ly/HqnfYb>.



Attending the Zero Robotics 2011 finals are space tourist/video game entrepreneur Richard Garriott, and astronauts (in blue jackets, from left) Leland Melvin, MIT alum (Physics) John Grunsfeld, AeroAstro Professor Jeff Hoffman, and AeroAstro alum Greg Chamitoff.

5. Alliance formation: due to the limited competition time on ISS and the desire to provide this motivational experience to as many schools as possible, the finalists are required to form alliances. Each multi-school alliance aggregates the best algorithmic attributes from each school to create their code for ISS.

6. Semifinals: the alliances compete in a final round-robin of 3D simulations, to select the top alliances that will participate in the ISS finals. Each alliance submits a single piece of software, created by the collaboration of multiple teams. In this way, Zero Robotics encourages (and requires) collaboration between teams.

7. ISS finals: the finalists have two weeks to review their software for the ISS competition. Their final submission is integrated and packaged for the ISS. The finalists are invited to MIT to watch the live broadcast of the ISS competition, with real-time audio and video downlinks. Hundreds of students have attended the multiple ISS finals, with many more watching remotely through live webcast and NASA TV.

RELEVANCE TO RESEARCH

A goal of every Zero Robotics game is to be relevant to the research SPHERES was designed to accomplish: satellite formation flight, proximity operations, and time-fuel efficient maneuvers. The students are faced with real programming challenges, rather than video game style interfaces. In addition, all the games must respect reality, because they take place using the physical limitations of the SPHERES satellites. To this end, the Zero Robotics team at MIT developed age-appropriate tutorials for physics, math, programming, logic, strategy, etc. to promote learning while competing.

Zero Robotics is run as part of the Space Systems Lab's research program where it's managed by AeroAstro graduate students. They perform most of the technical tasks to enable programming SPHERES online. In addition, Zero Robotics employs approximately two-dozen undergrads through the MIT Undergraduate Research Opportunities Program. These UROPs, as the undergrads are known, help with game design, programming, and simulation; mentor middle school

students; and support the high school program. Their participation is essential: UROPs are the ones who best understand how today's middle and high schools work and how to peak their interest and involvement. With the skills they've develop as mentors, the UROPs move on to become effective STEM teachers.

Next year's event is expected to attract between 300 and 400 schools worldwide. The marriage of SPHERES, ISS, and STEM education provides an exciting and rare opportunity to motivate the next generation of computational thinkers by allowing them for the first time, in the words of alum Erica Wagner, SM '02, PhD '07, former X PRIZE Lab@MIT director, to "actually touch space." →

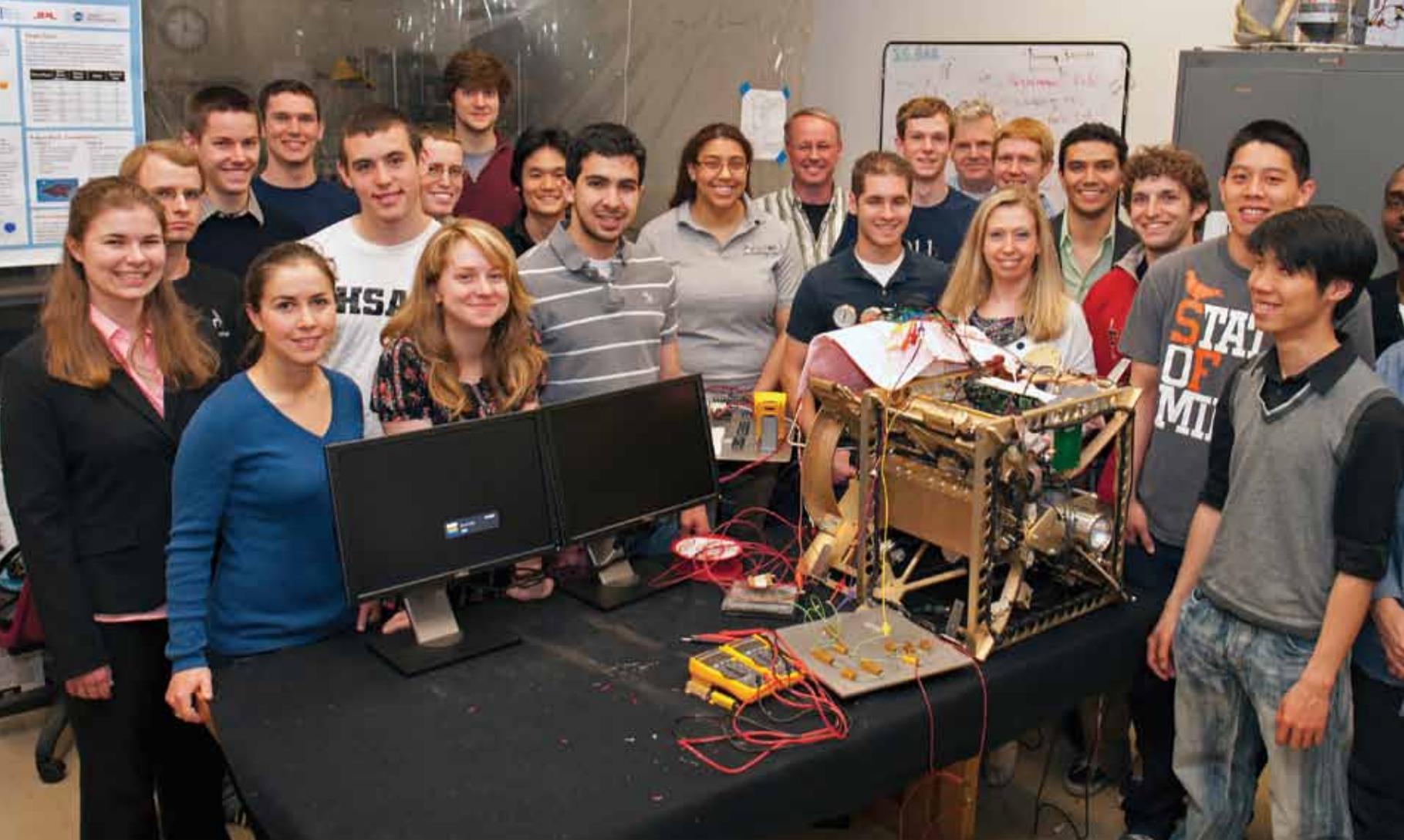


2011 Zero Robotics winning team "LCA ZeroBotX," from Lexington (Massachusetts) Christian Academy. On the lower left is SPHERES lead scientist Alvar Saenz-Otero, and in the upper right in the white sweatshirt is SPHERES senior Ph.D. student and Zero Robotics program lead Jacob Katz.

ALVAR SAENZ-OTERO is the Space System's Lab associate director and the SPHERES lead scientist. He was the lab teaching assistant for the class that built the original SPHERES satellites, and has led SPHERES ISS and ground-based research since 2005. He may be reached at alvarso@mit.edu.

JACOB G KATZ is the SPHERES team's senior PhD student, the Zero Robotics program lead, and designer of the Zero Robotics architecture. He may be reached at jgkatz@mit.edu.

DAVID W. MILLER is the Space Systems Laboratory director of the MIT and SPHERES team principal investigator. He has led all the CDIO Capstone Laboratory classes since 1999, including the SPHERES class, and continues to promote student built-satellites. He may be reached at millerd@mit.edu.



Industry and academic stakeholders are concerned that students, like these AeroAstro undergrads and grads working on a nanosatellite project, will find aerospace engineering careers as attractive as their options in other industries. However, a study indicates students feel other industries do better when it comes to job attributes of location and work/life balance.

Inspiring, educating, recruiting the future aerospace workforce

By Annalisa Weigel

There is nothing quite so annoying to an MIT faculty member as a discussion without data, especially on topics of real importance.

Such was the case in 2005 when I became involved in the national aerospace workforce policy discussions at conferences and symposia around the country. University engineering enrollments were dropping, and the

large workforce hired during the Apollo years was getting ready to retire. Who would replace them? Would the new recruits be just as excited (motivated?) as their predecessors? How would we recruit and retain the next generation of our aerospace workforce? There were anecdotes galore and much hand wringing over what the future holds for the makeup and quality of the aerospace workforce, but real data, aside from university enrollment and graduation rates, were conspicuously missing. Being from MIT and, thus, naturally having an inclination towards data, I decided that I would do my part to help interject data into our national discourse on the future aerospace workforce.

THE SURVEY OF AEROSPACE STUDENT ATTITUDES

In 2007, a project called the Survey of Aerospace Student Attitudes was born at MIT. Several MIT undergraduate UROPers, graduate students, and post docs all volunteered their time to help make this project a reality. Designed to collect attitudinal data from current sophomore and senior aerospace engineering undergraduate students around the country, the survey data would help the aerospace community understand how its next generation is inspired, educated, recruited, and retained.

An 18-month effort of background research, focus groups, and instrument design, testing and refinement yielded a 30-minute web-based survey instrument that gathers data in six areas: (1) initial pre-college interests in aerospace, (2) college experiences, (2) career expectations, (4) desired job attributes, (5) perception of the aerospace industry, and (6) demographics. It is envisioned that over time, a true longitudinal data will be created by surveying these now former students three and five years out from graduation, showing how attitudes, aspirations, and values of the younger aerospace workforce change over the remarkably dynamic times between selecting a major, completing university studies, and accepting first, and likely second jobs.

In 2009, the survey project collected data for the first time. More than 600 students participated from 22 colleges and universities around the United States. Respondents were about 80 percent male and 20 percent female, about 95 percent US citizens and 5 percent foreign nationals, and about 75 percent Caucasian and 25 percent non-Caucasian. This demographic makeup is representative of the population under study, and subsequent years of data gathering saw similar response characteristics.

To put the survey project in perspective, we honestly didn't know when we started if we would be successful. Getting data was dependent upon cooperation from leaders at aerospace engineering departments around the country to get the word out to their students to participate, and cooperation from students to fill out the long survey instrument. We were more than pleasantly surprised with the student response rate, which exceeded our expectations. And, as we began to analyze the data, we were amazed at both the insights we were extracting and the richness of the large data set collected.

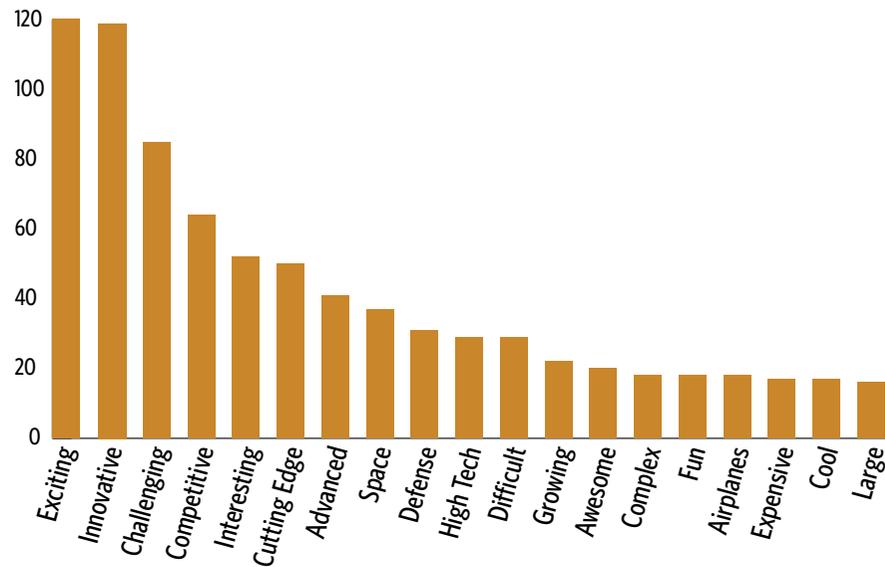
Following are just a few highlights of the results to date in the areas of inspiring, educating, and recruiting the future aerospace workforce.

INSPIRING

The first survey question was "Using the first one, two, or three words that come to mind, how would you describe the aerospace industry?" The answer was free form and not a multiple choice. As shown in the histogram of responses, aerospace is "exciting" to our students ... literally!

“Innovative” and “challenging” round out the top three words cited. While the word “challenging” could be seen as either (or both) positive or negative, “exciting” and “innovative” have clear positive connotations. Inspiring words stand out in how students describe the aerospace industry, which should be received as good news.

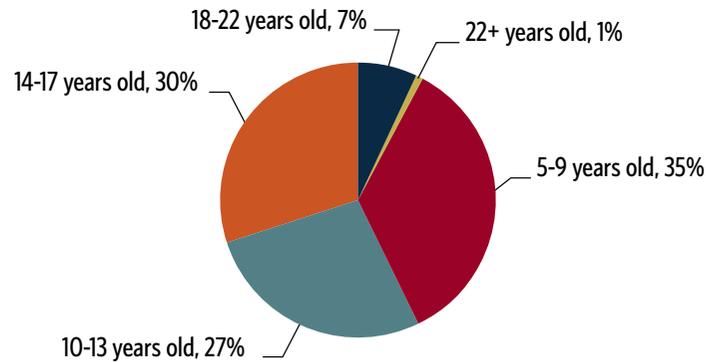
AEROSPACE IS EXCITING...LITERALLY!



When did aerospace engineering students first become interested in aerospace? We might have wondered if there was a magical age at which most students were first inspired about aerospace. If that were the case, that age band would be a logical place to invest the aerospace community’s scarce resources to create a greater interest among young people in aerospace careers. However, that turned out not to be the case. What we found is that first interest in aerospace can occur fairly uniformly at any point during students’ primary and secondary school experience. However, when correlated with students’ impressions of the aerospace industry during college, we see a particular statistically significant link. Students who first became interested

in aerospace before entering high school were more likely to have a positive impression of the aerospace industry during college than those who first became interested during high school. We wonder if the interest in aerospace forged at an earlier age creates a more endearing and enduring connection to our community. Perhaps what excites younger children about aerospace is different than what excites older children, and perhaps this difference has a connection to thinking more favorably about the industry later in life. Further analysis of the survey data set to help explain this particular result is ongoing.

AGE OF FIRST AEROSPACE INSPIRATION, N=426



First interest in aerospace can occur at any point during primary and secondary school.

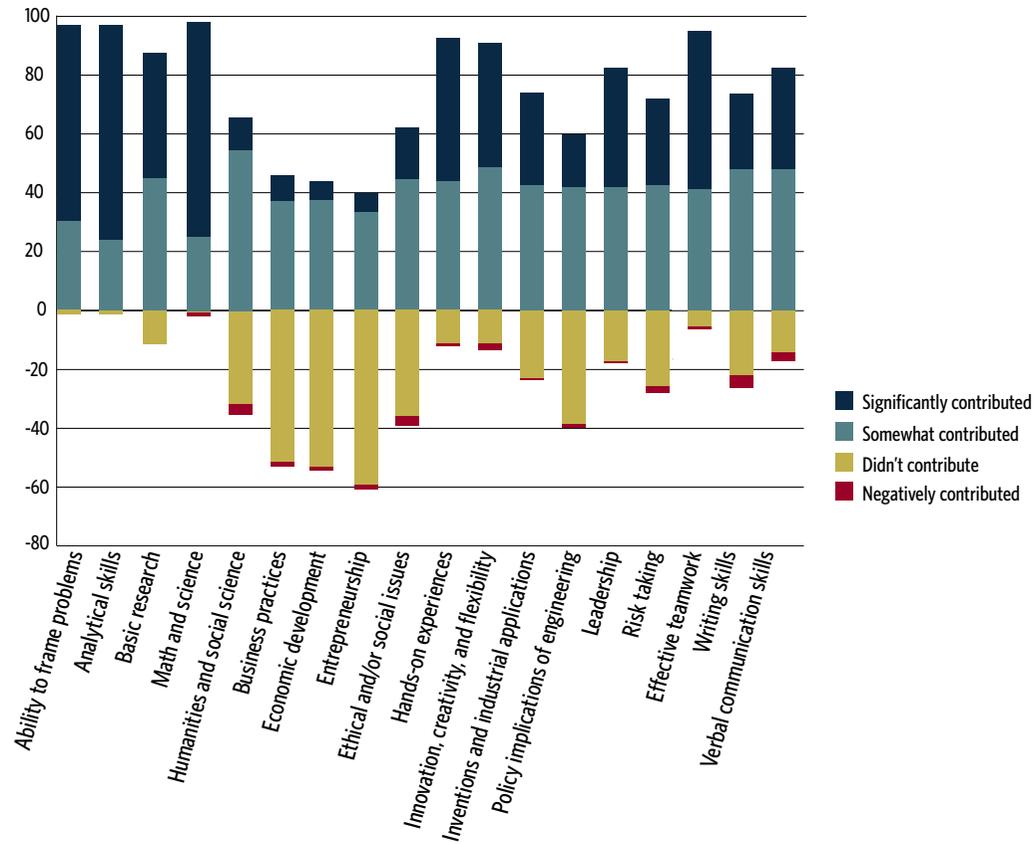
EDUCATING

The National Academy of Engineering's seminal 2004 report *The Engineer of 2020: Visions of Engineering in the New Century* presented several key attributes that will support the success and relevance of the engineering profession in 2020 and beyond. Those attributes are listed on the X-axis of the chart on page 35. We were curious to see how aerospace engineering students thought their college or university experiences contributed to their skills and experiences in those attributes. The traditional strengths of engineering education—ability to frame problems, analytical skills, basic research, math and science—are largely assessed by the students to have been positively developed during their time at university. And, it is encouraging to

see the additional communications, leadership, and teamwork skills that were added to most engineering curriculums in the 1990s and 2000s showing strongly as well. Where there is still progress to be made on the grand vision from *The Engineer of 2020* report is in areas related to business, economics, entrepreneurship, ethics, and policy implications. Improving in these areas might bring to mind innovative partnerships with industry and government to provide students with some hands-on experiences.

PROGRESS TOWARDS THE ENGINEER OF 2020

How has your college time contributed to your skills and experiences in the following areas? (n = 506)



RECRUITING

Even if the challenges of inspiring more young people to study aerospace were surmounted, and the current skills shortfall in students' education for the real engineering challenges of this new century were remedied, there may still exist issues with recruiting the best and the brightest into the aerospace industry upon graduation. In today's global economy, nearly every industry recognizes the valuable skills an engineering education gives a potential employee,

and these industries are hard at work recruiting our aerospace engineering students to join. So, we crafted part of the survey to address issues of aerospace industry perceptions, and career and job expectations.

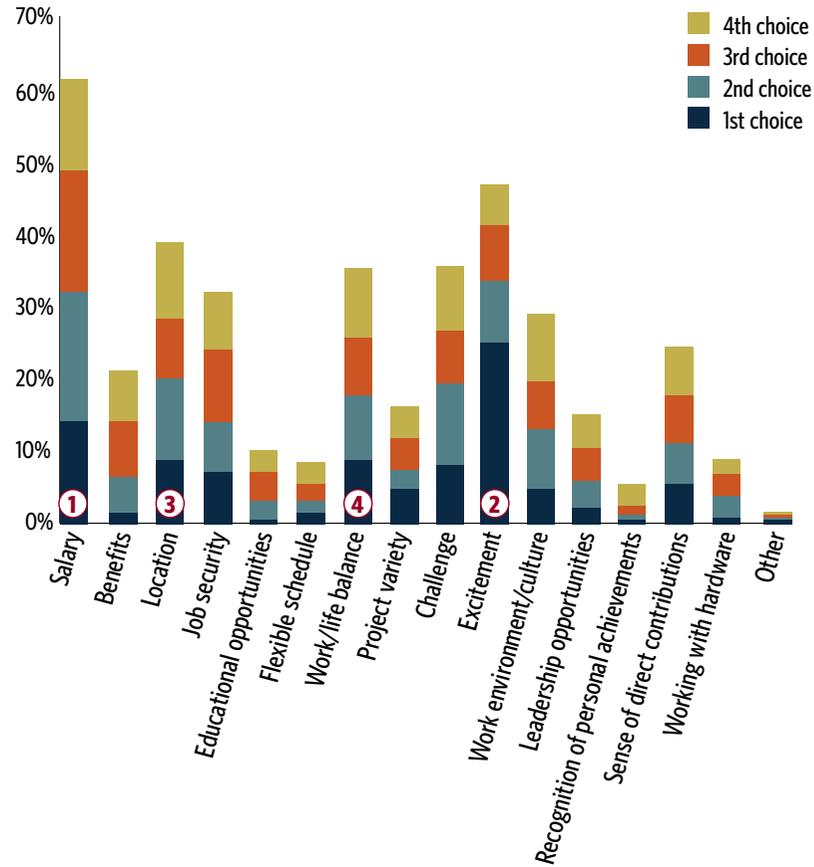
Students felt non-aerospace industries do better when it comes to job attributes of location and work/life balance.

Students were given a list of job attributes and asked to rank their top four choices. We found that students' top job attributes in order of preference were: 1) salary, 2) excitement, 3) location,

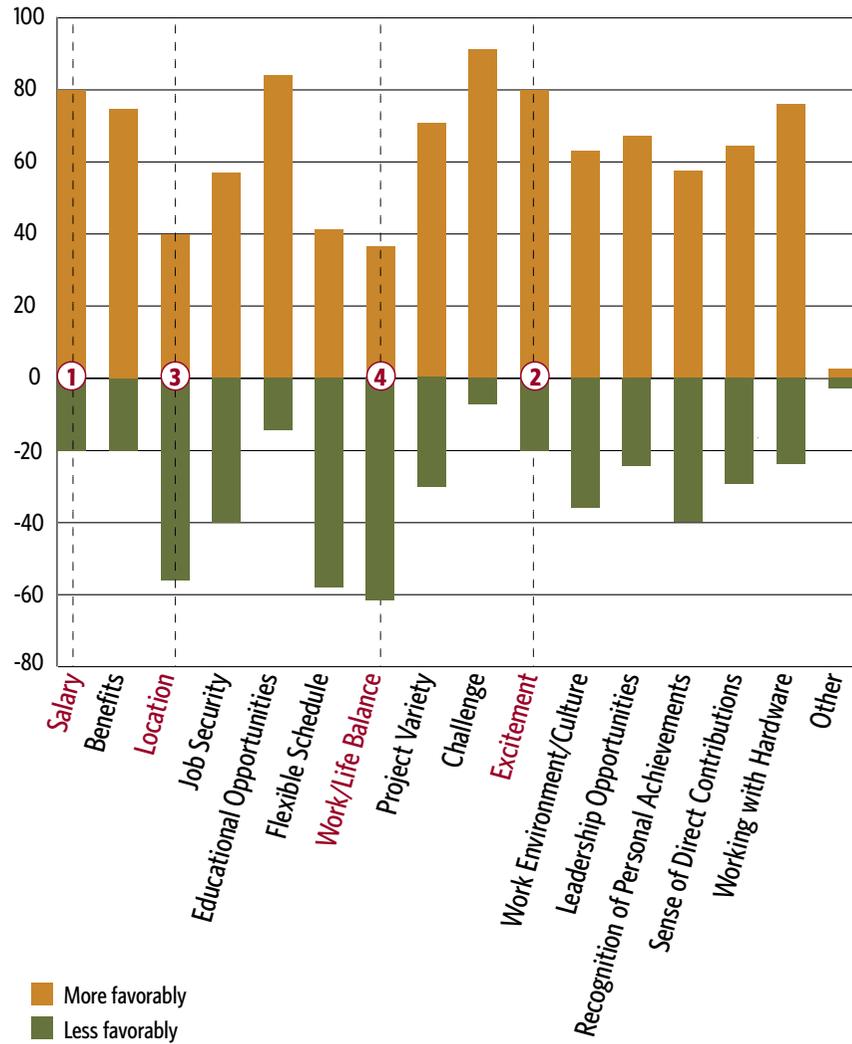
and 4) work/life balance. We then asked the students how they think aerospace compares to other industries on those same job attributes. Students felt that aerospace compared more favorably to other industries on the job attributes of salary and excitement. However, students felt other industries did much better when it came to job attributes of location and work/life balance. If location and work/life balance are important factors in choosing between job offers, the aerospace community may stand to lose some of its best and brightest to other industries that appear more attractive in these areas. It may prove useful to have a community dialogue on how aerospace can become an even more attractive industry to our graduating students choosing among job offers.

STUDENT RANKING OF VARIOUS JOB ATTRIBUTES, N=460

Please rank your top four job attributes. (n = 476)



HOW THE AEROSPACE INDUSTRY COMPARES TO OTHER INDUSTRIES ON VARIOUS JOB ATTRIBUTES



The brief insights presented above are just the beginning of what can be learned through more detailed analysis of the data gained from the Survey of Aerospace Student Attitudes project. Much work remains ahead for the project, as it moves from its initial all-volunteer efforts into an ongoing, concerted and resourced data analysis stage. Collaborators and sponsors are always welcome to join the effort. For more details on the survey project, a complete copy of the survey instrument, and analysis reports, visit <http://web.mit.edu/caspar/aerosurvey>. ➔

ANNALISA L. WEIGEL is an MIT AeroAstro assistant professor of aeronautics and astronautics and the Survey of Aerospace Student Attitudes Project principal investigator. She chairs the American Institute of Aeronautics and Astronautics Subcommittee on Workforce and Education, and a Workforce Development Program Committee of the International Astronautical Federation member. She frequently speaks at conferences and meetings on the topic of our future aerospace workforce. Weigel may be reached at alweigel@mit.edu.



FACULTY INTERVIEW: RUSSIAN AROUND WITH ED

AeroAstro Professor Crawley is now President Crawley of Russia's Skolkovo Institute

By Richard Dahl

AeroAstro Professor Edward Crawley has held many important positions over the course of his 32-year career in academia, but his newest venture may be the most exciting and demanding one yet.

Late last year, the new Skolkovo Institute of Science and Technology in Russia announced that the 56-year-old AeroAstro Professor Edward Crawley had been selected as the school's first president. In announcing the decision, Skolkovo Foundation President Viktor Vekselberg said that Crawley was the "number one candidate" for the job because of his stature at MIT and as an expert in space exploration as well as for his strong connections to Russia, his fluency in the Russian language, and his reputation as a pioneer in commercializing science. Construction of the school's campus has begun and the Institute is scheduled to open in 2015.

Crawley's connection to MIT extends back to his undergraduate years and has remained uninterrupted. After receiving his Sc.D. in 1980, he joined the AeroAstro faculty and went on to develop MIT's System Design and Management Program before serving as AeroAstro head for seven years then three years as director of the Cambridge-MIT Institute, and then as director of the Gordon-MIT Engineering Leadership Program. And in 2011, Crawley won the prestigious Bernard M. Gordon Prize for Innovation in Engineering and Technology Education for his creation of the Conceive, Design, Implement, Operate (CDIO) educational initiative for producing the next generation of engineers.

AeroAstro sat down with Crawley to talk about the challenges lying ahead in Russia.

AeroAstro: Could you provide some background on the Skolkovo Institute and how you came to be named as its president?

Crawley: The motivation for this institute is very simple. The Russian Federation economy largely runs on raw materials — gas, oil, precious metals — and the government realizes that while they still have revenue from these natural resources, they have

to transform their economy to more of a knowledge — and manufacturing-based economy. So how do you do that? Well, you take the existing institutions and you move them in the right direction; but you also create some new institutions. So they created the approach, which in China would be called a special economic zone — a region that has special economic status — called Skolkovo, just outside the Moscow city limits, and we're building in Skolkovo the entire ecosystem of innovation. We're attracting multinational research and development research centers to locate there, there's funding through the Skolkovo Foundation to create small and medium-sized enterprise entrepreneurship there, there's going to be good schools, nice housing, and it's going to be an area of intense economic growth that will hopefully drive the regional economy; and if it succeeds they'll replicate it elsewhere.

The conventional wisdom is that at the center of every one of these is a great research university. So, basically, the Russian Federation government decided it wanted a graduate research, science, and engineering university to be at the center of this region of economic growth. They went around the world to a limited number of universities and said would you like to help us do this? And they made a deal with MIT.

This is not the first time MIT has done something like this in the last decade. (In addition to the Cambridge-MIT Institute, MIT has joined similar ventures in several other countries, including Singapore, Malaysia, and Portugal). So if you want the university to sort of look and feel like MIT, you've got to have as its leader someone who's willing to accept that and not push back and say, 'Oh, we can't do that here.' Therefore, you either get an MIT person to go be the founding president or you get some-

body who acts and thinks like an MIT person — who might have been at MIT earlier, or Stanford, or one of these other great innovation-intensive universities around the world. The Skolkovo Foundation did a search and ended up asking me to be president.

AeroAstro: Could you describe your prior connections in Russia?

Crawley: Well, by the time I was 13 or 14 years old I knew I wanted to be an aeroastro person — particularly an astro guy, a space guy — and by the time I was 15 or 16 I knew that my ambition in life was to unite the Soviet and American space programs. We can date that because I started studying Russian as a sophomore in high school. I decided to study Russian so that I could help unite the Russian and American space programs.

AeroAstro: So this was during the Space Race.

Crawley: It was 1969, the same year we put someone on the moon and a good year to decide that you wanted to be in the space business. So when I came to MIT I chose to live in the Russian-speaking dormitory, and I spent one semester in the Soviet Union in Leningrad. Then I came back and did my doctoral work and joined the faculty and one day in 1985, I get this call from the Russian Academy of Science's Space Research Institute that said, 'Professor Crawley, we'd like to you come to Russia.' From 1985 to 1990, I went about every year and I visited Russian institutions and gave lectures and sort of helped build bridges between the then-Soviet aerospace-space infrastructure, companies and universities, and their counterparts in the U.S. Then in 1993 I was a member of the Presidential Commission on the International Space Station and lo and behold, as a result of

that, we proposed to bring together the Russian and American space-station programs. We weren't the only ones advocating that and we weren't necessarily the instrumental ones, but we certainly went on record as a presidential commission saying we should do that.

As a result, I spent a modest amount of time in Russia and I have residual contacts there. So 20 years go by, they're looking for a rector of a new Russian university, and they call me.

AeroAstro: What will the institute do?

Crawley: The institute will be focused on the three functions of a modern, 21st century university: developing new knowledge (discoveries, research), producing talent (education), and producing tangible goods and services and contributing to the production of tangible goods and services through innovation. The real intellectual question is: How do you create a university from scratch knowing that it's supposed to be about the development of all three of these strands? That's the challenge we have.

AeroAstro: What's your biggest priority right now in the development of the institute?

Crawley: The students will come. The real challenge is attracting the faculty. If you're a young or mid-career faculty member who, at least in principle, could have a position at any major university around the world, why would you move to Moscow? So that's what I have to convince them of.

The effort that's going to be required to create a new university in a foreign country is enormous. One of the things that I find interesting about this job is that it challenges just about every

dimension of my personal capabilities. I have to be able to lecture to students and entertain them, I have to be able to recruit faculty, I have to be able to build new organizations, and then I have to turn around and set up the endowment fund. Well, there are no university endowments in the Russian Federation; so we have to establish new laws governing endowments for universities in Russia.

AeroAstro: How do you do that?

Crawley: Well, you sit down with the guys in the state duma and you figure out how to draft the law. And then you have to go and find a fund manager. Of course, there are no university-endowment fund managers in the Russian Federation because there are no university endowments. So how do you qualify a fund manager? Well, it just so happens that because my wife is in the financial business, I happen to know a little about this stuff by osmosis at the dinner table. And then I have to build a \$1-billion physical plant. The physical plant of Skolkovo Tech will more than re-create the central complex of buildings at MIT. I'm building Cal Tech in one fell swoop. Three hundred professors, 190,000 square meters. Then you've got to go talk to the government because this is a major government project, so you've got to meet with prime ministers and deputy prime ministers because they're the people who are sponsoring this project—but I've had a little experience doing this in Washington and in London. And then, this amazes me, but I'm sort of a celebrity in Russia. An American who comes to Russia to start a new university is a novelty. So I'm constantly being asked by the media there to do interviews, including stand-ups on Russian evening TV. In Russian.

AeroAstro: How much time are you spending in Russia?

Crawley: I'm spending about two weeks out of every four there. I spend about a week here at MIT because of course MIT is the major partner. And then I spend about a week on an airplane.

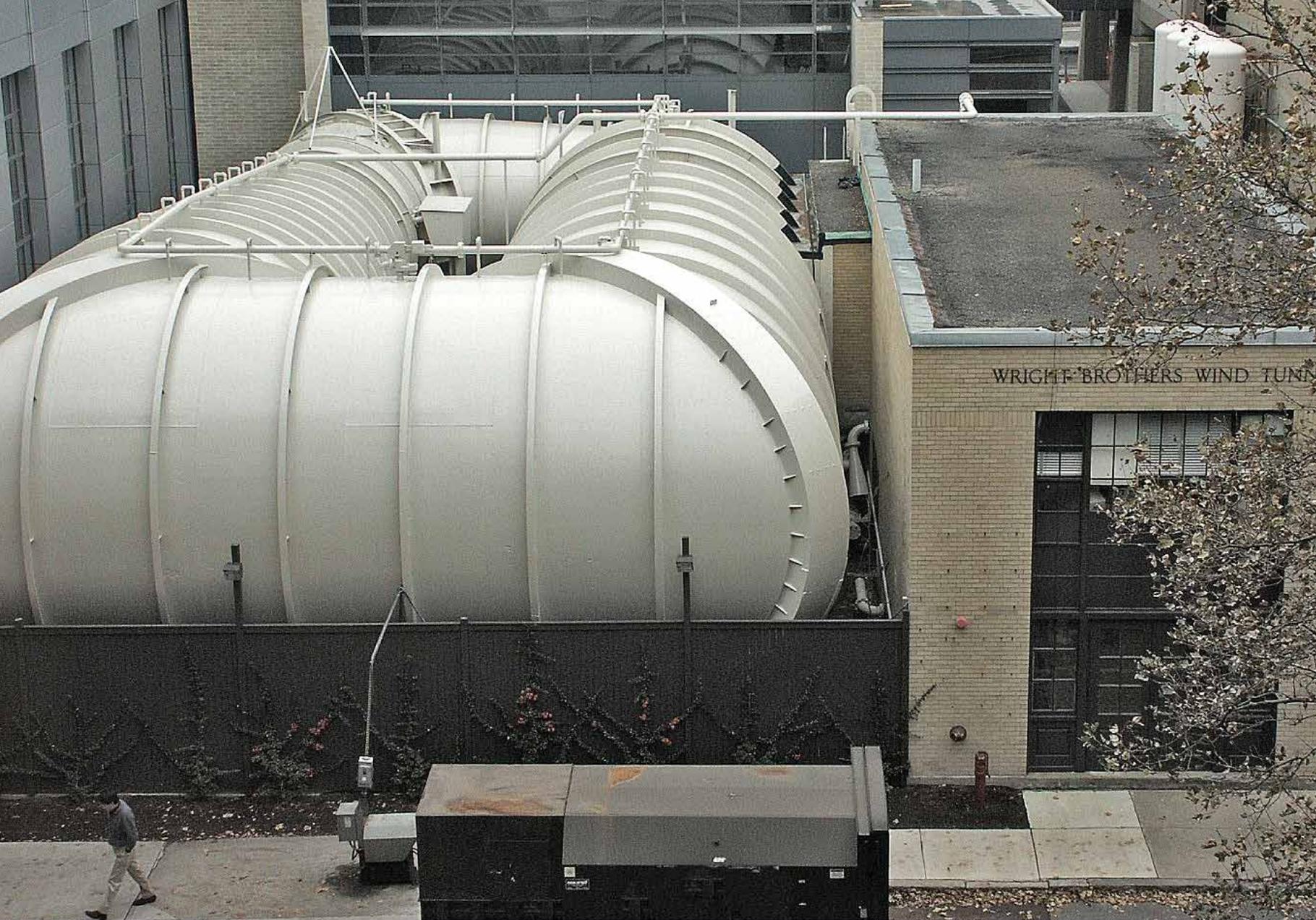
AeroAstro: During your career at MIT, did you ever envision taking on something like this?

Crawley: One of the great things about being a university professor, especially at MIT, is that you can just reinvent yourself. If you look at my career, it's sort of been in four- or five-year chunks. The first four or five years I did what I was hired for: gas turbine engine structures. Then by '85 I had sort of drifted off to working on space structures and dynamics and control and I did that until the early '90s. Then, from then until about 1995 I worked on creating the SDM (System Design and Management) program and then for seven years I became the department head and then for four years I ran the Cambridge MIT Institute and then for four years I worked on creating the Gordon Engineering Leadership Program and now I'm the president of a university in Russia.

AeroAstro: So what chunks do you envision ahead?

Crawley: Oh, I just started this one. The effort that's going to be required to create a new university in a foreign country is enormous. →

RICHARD DAHL is a journalist and freelance writer, and a frequent contributor to AeroAstro. He may be reached at cdahl16@gmail.com.



The iconic Wright Brothers Wind Tunnel, opened in 1938 and in daily use nearly 75 years later.

The timeless tunnel

By William T.G. Litant

Seventy-five years ago, MIT authorized construction of the Wright Brothers Wind Tunnel. Today, the iconic facility continues in high demand for teaching and research.

There's no shortage of MIT Aeronautics and Astronautics icons: Jimmy Doolittle, Doc Draper, the

Daedalus human-powered aircraft, the Apollo guidance computer. But of all our historic symbols, there's one that maintains a vital role in the department and will likely do so well into the future: The Wright Brothers Wind Tunnel.

Since September 1938, when it was dedicated during the Fifth International Congress of Applied Mechanics, the WBWT has played a major role in the development of aerospace, civil engineering, and architectural systems. From its early days during World War Two, when technicians worked in two shifts on military aircraft design, testing has evolved to today's examination of ground antenna configurations, aeroelastic dynamics of airport control tower configurations, ski gear, space suits, bicycle and motorcycle configurations, subway station entrances, ship sails, wind turbines, and, most recently, an AeroAstro design for a clean, quiet, and super-efficient commercial aircraft.

THE TUNNEL IS BORN

Wind tunnels have been used for MIT thesis research since at least 1896 when student Albert Wells spliced a tube to the school's ventilation system so he could study the effects of air movement on different surfaces.



The D-8 “double-bubble” aircraft, a AeroAstro design for a super-efficient, clean, and quiet commercial airliner, is positioned in the tunnel in 2010. Larger models of the aircraft are scheduled for testing beginning in mid-2012.

As MIT began its move from the original Boston campus to the city of Cambridge, the Institute’s first lab to open on the west side of the Charles was a wind tunnel, located on Vassar Street, and constructed by Jerome Hunsaker, assisted by his recently-graduated assistant Donald Douglas (who would eventually found the Douglas Aircraft Company). The facility consisted of a square wooden tunnel attached to a sheet metal cylinder. Inside was a seven-foot black walnut propeller and chain-driven motor. According to MIT archives, aeronautical testing was the tunnel’s main purpose, but it was also used to measure the effects of wind pressure on architectural models, rates of evaporation from reservoirs, and air resistance of such diverse objects as automobiles, golf clubs, and tennis rackets. The Army Air Service leased the tunnel in 1917 where it tested nearly every World War I plane design prior to production.

By 1933 when Jerome C. Hunsaker became Head of the Mechanical Engineering Department and its aeronautical engineering program, several tunnels were available on campus for instruction and development testing. These were limited to speeds and Reynolds numbers far below those of contemporary aircraft, such as the Boeing B-9 bomber and Douglas DC-2. The need for a modern tunnel was clear.

In 1935, a design emerged for a new tunnel. It would feature a closed single return circuit with an elliptical operating test section 7.5 feet by 10 feet, all enclosed within an outer steel shell that would allow pressurized tunnel operations offering variable Reynolds number capability. The driver was a 2,000 horsepower, pole-changing induction motor spinning a controllable pitch 13-foot diameter fan.

The MIT Corporation approved construction of the tunnel on May 12, 1937 and decided it would be called the Wright Brothers Memorial Wind Tunnel. Initial cost was approximately \$230,000, half of which came from funds solicited by Hunsaker. Gifts totaling \$92,000 were received from a donors list that included automotive and aviation pioneer Vincent Bendix, Cabot Corporation founder Godfrey L. Cabot, and the Curtiss-Wright Corp.

The structure was filled with water for pressure certification on August 12, 1938 and dedicated five days later.

IMMEDIATE DEMAND

The first dozen years of operation included heavy World War Two demands from industry for design development testing. (A model generic fighter plane from the period still resides in the tunnel storage room.) Sikorsky, Grumman, Republic, Consolidated-Vultee, and Chance Vought were among the many companies that purchased tunnel time in the 1940s and 1950s. Pressure operations were concentrated at 2.5 atmospheres absolute and test velocity was held to 125 mph. Pressure limitations were related to practical pumping times; dryers were required to avoid wet air during compression, and too rapid decompression led to condensation. Third speed was avoided as a result of the excessive noise, but when necessary, was timed to meet the 10-minute breaks between classes. Fourth, or top speed was also avoided due to gyroscopic forces on the fan blades, which prevented pitch changes while running. Noise proved to be severe in fourth speed. Legend has it that the tunnel was only once tested at its maximum design speed of more than 400 mph, and complaints were received from downtown Boston about the noise.



Technical instructor Earl Wassmouth (left) and WBWT assistant director Frank Durgin study the effects on Lower Manhattan of the soon-to-be-constructed World Trade Center towers. (MIT Archives. Courtesy MIT Museum)

Legend has it that the tunnel was only once tested at its maximum design speed; complaints were received from downtown Boston about the noise.



One of the most unusual tests in the Wright Brother's Wind Tunnel was conducted in 2007. A 130 million-year-old fossil of a four-winged "microraptor" had been discovered in China. To determine how this unusual beast used its wings, the NOVA television program commissioned a replica of the creature and then, working with AeroAstro, tested it in the tunnel. The results were featured in the 2008 NOVA program "The Four-Winged Dinosaur."

Professor Dave Darmofal agrees. "I think it's safe to say that over at least the last dozen years, virtually every AeroAstro student has been inside the WBWT and used it in multiple classes: for example, Unified Engineering, Aerodynamics, Experimental Projects, and Flight Vehicle Dynamics," he says.

In 1972 the facility took on simulations to explain window failures in Boston's new John Hancock Tower. Following the project's success, an initial design evaluation assignment was awarded to establish the wind effects on the facade and at ground level for the Sears Tower (now the Willis Tower) in Chicago, along with a number of other ground studies such as radome housings, the World Trade Center Towers in New York, antenna configurations, galloping power transmission lines, and tall structures in Cincinnati, Columbus, Orlando, Toledo, and Boston.

A HEAVILY USED ICON

While its systems are showing their age, the tunnel is still heavily used as a valuable research and teaching tool.

"There's a strong need for the tunnel for student projects," says Professor Mark Drela, who's been using the facility since he was a student in the early 1980s. "A large fraction of undergrad thesis and coursework is done there. While we can do a lot of computer modeling, the faculty still find the tunnel extremely important."

Most recently, a faculty-student team has been in the tunnel running NASA-funded tests of the D-8, an MIT design for a 737-sized commercial aircraft that is not only quieter and cleaner than today's planes, it could offer as much as 70 percent better fuel efficiency. Also, a commercial outfit is testing a unique wind turbine designs, and not a week goes by without a request from other MIT departments and external researchers for tunnel time.

Drela also emphasizes that the tunnel is a symbol of the department. During the 2010 MIT 150th anniversary open house, the WBWT was one of the Institute's most popular attractions; the line of visitors stretched down the building stairs, out the door, past the Building 33 hangar, under the Building 35/37 connector, and out to Vassar Street as people waited for a turn to stand in the test section and experience the "blast" (which was kept to a rather sedate 20 mph breeze). For more than an hour after the day's activities ended elsewhere on campus, AeroAstro senior technical instructor Dick Perdichizzi kept the tunnel open as visitors kept arriving. He doesn't know how many people passed through, but he says, "It was definitely in the thousands."

AeroAstro faculty would like to see the tunnel modernized, ensuring its viability for years to come. "The motor and the electricians are the original World War Two vintage," Drela says. "The motor is a constant-speed design, meaning you select what

Wright Brothers Wind Tunnel

- » Closed return, continuous flow circuit.
- » Characteristics (for one atmosphere operation, 80% power)
 - Mach number: 0 to 0.25
 - Reynolds number: 0 to 1.8×10^6 per foot
 - Dynamic pressure: 0 to 67 psf
 - Temperature: 0 to 100°F
 - Test region: 10 ft x 7.5-ft elliptical section, 15 ft long
- » Data acquisition system includes a force balance linked to computer systems for recording, storing, and examination on line of raw, reduced or graphically displayed outputs.
- » 32 channel digital data recording
- » Multiple user facilities permit simultaneous data comparison or manipulation, and related computing for analysis.
- » Pressure measurement systems include three computer-controlled Scani-valves and Setra transducer with flat frequency response to 800 Hz.
- » External six-component main mechanical balance for strut-mounted models with lift loads to 3000 lbs. Internal strain gage balances for sting mounts, model components, etc. for loads to 100 lbs.
- » Auxiliary air supplies for propulsion units, injection, boundary layer control, etc.
- » Continuous flow rates of 1.5 or 0.5 lb/sec at 60 or 125 psi respectively, intermittently 4 lb/sec at 100 psi, and 9 lb/sec at 22 psi.
- » Gust generator system for longitudinal and horizontal gusts. Approximately sinusoidal to 60 Hz, strength inversely proportional to air speed.
- » Flow visualization with surface oils, attached tufts, smoke, photography.
- » Supporting shop facilities.



Senior technical instructor Dick Perdichizzi in the depths of the Wright Brothers Wind Tunnel with the vintage 1938 2,000 horsepower pole-changing induction motor. The fan is 13 feet in diameter and the blade pitch is adjustable.

speed you want and the motor immediately tries to attain it. You can't ramp it up," Drela says. "It starts with an enormous surge of power and is pretty inefficient." In fact, the WBWT operator has to call the power company before the tunnel is fired up. "We could blackout this part of Cambridge if we didn't let them know," says Perdichizzi.

The tunnel also has a tendency to get hot, especially when running at higher speeds in summer months when temperatures inside the test section can reach 100 degrees Fahrenheit or higher. This not only changes the air density, it's a challenge for those working in the test section where it gets well over 100 degrees Fahrenheit. "It's like a sauna," Drela says. In its early days, the tunnel was cooled by flooding the exterior with water pumped from the nearby Charles River. Drela would like to see installation of a cooling system. With that, and some improvements to the vanes that direct the air stream around the tunnel corners, tests could be conducted at speeds of 200 mph or more — maybe even up to the original 400 mph intent. Modern fan blade designs would also help reduce operating noise.

Another thing Drela, Perdichizzi, and others would like to see is modernizing of the data collection equipment, much of which dates back to the 1980s. “What we have works, but updating would greatly accelerate testing,” Drela says. “And, if something breaks it’ll be a challenge to replace.”

The AeroAstro Department has formed a wind tunnel committee to ascertain exactly what WBWT upgrades are required, and to solicit resource contributions, both hardware and financial. “We’re doing an extensive assessment of the tunnel’s needs to ensure it continues in its role long into the future,” says Darmofal, who heads the committee. “But we can’t do it all on our own, which is why we’re encouraging, and counting on, alums and industry friends to come forward to support this.”

“I think people will be pleased to help out,” Darmofal says. “After all, the Wright Brothers Wind Tunnel is an old friend to a lot of us.” →

Parts of this article originally appeared in the *The Wright Brothers Facility* (1990), courtesy of the MIT Museum. The author is unknown; we will be glad to credit the author if he/she can be identified.

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TO LEARN HOW YOU CAN SUPPORT UPDATING THE MIT WRIGHT BROTHERS WIND TUNNEL, CONTACT AEROASTRO DEPARTMENT HEAD PROFESSOR JAIME PERAIRE AT PERAIRE@MIT.EDU.



Jon Gibbs observes a blending wing aircraft model undergoing testing in the Wright Brothers Wind Tunnel. Virtually every AeroAstro student spends time learning how research is conducted in the tunnel.

Many young people increasingly are exposed only to a virtual representation of the physical world. AeroAstro faculty, like Oli de Weck, here setting up a water jet cutter in the department's Gelb Lab, are exposing students to a wide range of hands-on experiences.



Evolution: aerospace manufacturing, the U.S. economy, and MIT's role

By Olivier de Weck

In 1989, MIT published the influential book “Made in America — Regaining the Competitive Edge.” The book discussed the need for American industry to increase industrial productivity to better compete with international firms.

At that time, Japan was successfully importing high-quality low-cost products in the automotive, semiconductor and consumer electronics sectors in the United States, and was rapidly gaining

market share. The data, conclusions, and recommendations in the book were the result of a monumental three-year effort by the MIT Commission on Industrial Productivity.

The response to the book was vigorous. It led to follow-on efforts such as implementing lean manufacturing techniques in many U.S. firms, increasing the output per worker; improving product design; and generally raising American manufacturing firms' performance levels. Despite these successes, today, many of the same issues persist, and, despite gains in the 1990s, there has been a precipitous decline in the U.S. manufacturing labor force, especially since the year 2000. Overall manufacturing output value-added in the United States is still about \$2 trillion per year and has also declined, but less dramatically. In part, the decline in the manufacturing laborforce is due precisely to the gains in productivity that had been called for in the 1989 report, but — and there is little controversy among economists about this point — much of the decline resulted from off-shoring of U.S. manufacturing activities to lower wage countries such as China and Mexico. Lower wage costs are not the only factor responsible for offshoring, others include better access to emerging markets, lower corporate tax rates, and targeted incentives and industrial policies by emerging producer countries.

AEROSPACE: A BRIGHT SPOT

In this climate of contracting manufacturing and progressive deindustrialization of the American economy, aerospace and defense manufacturing remains a bright spot and one of the few bastions of U.S. strength. In 2009, American aerospace manufacturing and parts production accounted for about \$100 billion in terms of its contribution to the gross domestic product and executed shipments valued at more than \$179 billion. According to the U.S. Census, in 2010 the United States produced 2,842 new aircraft including large transports, general aviation aircraft, rotorcraft, and military aircraft. More importantly, the United States generated a trade surplus of \$49.5 billion with aerospace products and services, up from \$26.8 billion in 2000. The aerospace industry has been one of the most positive contributors to the U.S. trade balance in recent years. Major product categories include the design and manufacturing of commercial aircraft, military aircraft, unmanned aerial vehicles, and commercial satellites and launch services, amongst others. These systems are becoming increasingly complex and capable of achieving efficient performance. The poster child for U.S. innovation in 2012 is the long-awaited commercial

launch of the Boeing 787 Dreamliner, which allows new profitable routes such as the direct connection between Boston and Tokyo, inaugurated on April 22.

It is positive that aerospace has truly become a global business, but it is essential for the U.S. to maintain its strength in this key industry.

However, continued strength in U.S. aerospace manufacturing is not guaranteed, and may erode if industry, government and academia do not collaborate closely in the future. Examples of where international manufacturers have been able to become increasingly competitive—in part due to support by their own

governments—are numerous. For example, Thales Alenia Space, a company located in France and Italy, was awarded the prime contract for designing the next generation satellite constellation, IRIDIUM Next, in 2011 for a total of 81 satellites and a contract value of \$2.1 billion. The manufacturer of the original Iridium constellation in the 1990s was Lockheed Martin with major manufacturing sites in Colorado and California. It is of course positive that aerospace has truly become a global business, but it is essential for the U.S. to maintain its strength in this key industry. Competition not only arises from Europe but also from newer aerospace producers such as Brazil and China. These emerging markets also represent important opportunities for export growth. Booz & Co recently charted which U.S. industries can best compete as exporters, which



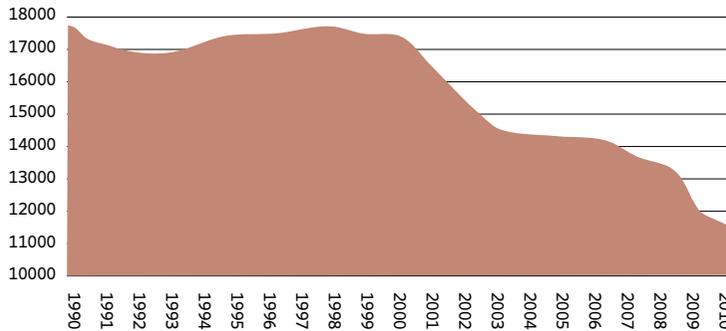
An example of high-level disruptive innovation in design and manufacturing is Terraugia's roadable aircraft "Transition."

can be dominant in the regional North American market, which can survive but are threatened by foreign competitors, and which are already mostly overseas but can still manufacture in the United States to serve niche markets. It is clear from this analysis that aerospace has a special role to play and must be maintained as a key industry in the United States.

What is needed is a reinvigoration and modernization of the U.S. aerospace and defense industry as well as the institutions that carry out advanced research and educate the workforce of the future. An example of an innovative new firm is SpaceX. SpaceX has achieved in a few years what many thought to be impossible, namely the design of two new launch vehicles essentially from the ground up, the Falcon-1 and Falcon-9 with an innovative low cost two-stage-to-orbit design. Again, related to Iridium NEXT, SpaceX was awarded a significant launch services contract for \$492 million for launches to be conducted between 2015 and 2017.

The future strategy for U.S. manufacturing must be to maintain high levels of disruptive innovation both in design but also manufacturing, while continuing to evolve and improve its strengths in high-value added industries, such as aerospace. An example of such innovation is the collaboration between human and robotic workers on the assembly line (see article by Julie Shah in this issue) as well as the creation of new types of products such as the Transition roadable aircraft developed in Massachusetts by Terraugia, a spinoff from the MIT AeroAstro Department. While government support of basic and applied research and its role as a lead customer and regulator is essential, it is incumbent upon industry and academia to provide the breakthroughs that will fuel future growth.

Decline in U.S. Manufacturing Employment (millions), 1990-2010



Despite gains in the 1990s, there has been a precipitous decline in the U.S. manufacturing labor force, especially since the year 2000.

MIT AND AEROASTRO'S ROLE

MIT and the Department of Aeronautics and Astronautics are global leaders in aerospace innovation and manufacturing research and are committed to conceptualization, design, manufacturing, and operation of complex aerospace systems. Through our educational and research programs we strengthen the U.S. manufacturing base. Increasingly, we see sponsors and students who want new designs implemented in practice and want to be able to rapidly prototype and test new aerospace vehicles and operational approaches. Consider the following three examples.

First, we have been, and continue to be, a major contributor to the DARPA META program, which is a part of the Adaptive Vehicle Make portfolio. The goal of this program is to achieve a factor of five compression in the time required to develop new aerospace systems. MIT faculty and staff have contributed new methods for abstraction-based design with “correct-by-construction” compositional rules, probabilistic design under uncertainty and are demonstrating that a 5x speed up in the design and manufacturing of complex cyber-electro-mechanical systems is indeed possible. We are working on implementing this new integrated approach in our Unified Engineering classes starting in the 2012-13 academic year. We expect that this new approach will make our students and teams even more competitive in future competitions such as the annual AIAA Design-Build-Fly competition.

Second, the CDIO (Conceive-Design-Implement-Operate) Initiative (<http://www.cdio.org>), an international consortium of universities collaborating to improve engineering education, continues to grow and now encompasses nearly 100 universities and programs worldwide. As part of this program MIT AeroAstro offers ambitious capstone design courses driven by real world challenges that expose our undergraduate and graduate students to the challenges of creating complex systems. An example of our commitment is the 16.810 class on Engineering Design and

Rapid Prototyping. In this class students learn how to deploy CAD/CAM/CAE methods and tools to rapidly develop new components and systems.

Third, our manufacturing research pushes the cutting edge by researching better ways in which the complexity of aerospace systems can be managed, how humans and robots collaborate, new types of advanced electric propulsion thrusters, innovative small satellite designs, and nano-enabled materials such as composites with embedded fibers for sensing and distributed control. In an era where many young people increasingly are exposed only to a virtual representation of the physical world, the excitement and real impact of aerospace manufacturing remains a viable and increasingly sought after field of research, an exciting career path, and a way to make crucial contributions to the U.S. economy and to that of other nations. We at MIT are excited to continue this journey with renewed energy and enthusiasm. →

OLIVIER DE WECK is an associate professor of aeronautics and astronautics and engineering systems, and executive director, MIT Production in the Innovation Economy Initiative. He may be reached at deweck@mit.edu.



Michael Klinker (left) and James Byron prep for flight the plane they designed and built in AeroAstro's Engineering Design and Rapid Prototyping Independent Activities class. In this class students learn how to rapidly develop new components and systems; they had one week to design, build, and fly the aircraft.

LAB REPORT:

A 2011-2012 review of Aeronautics and Astronautics Department Laboratories

Information provided by the research laboratories and centers.

In the Space Systems Lab, graduate students (from left) Eric Peters, Evan Wise, and Anne Marinan inspect the dual-spinning CubeSat, MicroMAS (the Microsized Microwave Atmospheric Satellite). This small satellite is the engineering model for the later flight model that will fly in space. The engineering model contains all of the systems required to operate the satellite: power, control, avionics, communications, and thermal subsystems. MicroMAS data will help researchers understand and predict tropical storms and hurricanes.



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AEROSPACE COMPUTATIONAL DESIGN LABORATORY

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

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

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

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

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

Visit the Aerospace Computational Design Laboratory at <http://acd.l.mit.edu>

AEROSPACE CONTROLS LABORATORY

The Aerospace Controls Laboratory researches autonomous systems and control design for aircraft, spacecraft, and ground vehicles. Theoretical research is pursued in areas such as decision making under uncertainty; path planning, activity, and task assignment; mission planning for unmanned aerial vehicles; sensor network design; and robust, adaptive, and nonlinear control. A key aspect of ACL is RAVEN (Real-time indoor Autonomous Vehicle test ENvironment), a unique experimental facility that uses a motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and aircraft, and robust coordination algorithms for multiple vehicles. Recent research includes the following:

Robust Planning in Uncertain Environments: ACL developed a distributed task-planning algorithm that provides provably good, conflict-free, approximate solutions for heterogeneous multiagent/multitask allocation problems on random network structures. The consensus-based bundle algorithm has since been extended to include task time-windows, coupled agent constraints, asynchronous communications, and limited network connectivity. CBBA has been used to plan for both networked UAV/UGV teams and human-robot teams, and real-time performance has been validated through flight test experiments. Recent path planning research has yielded chance constrained rapidly-exploring random trees, a robust planning algorithm to efficiently identify trajectories, which satisfy all problem constraints with some minimum probability. Finally, in collaboration with Professor Nick Roy's group, ACL developed an efficient approach for modeling dynamic obstacles with uncertain future trajectories, through the use of Gaussian processes coupled with an RRT-based reachability evaluation. ACL is involved in a multi-year MURI focused on enabling decentralized planning algorithms under uncertainty. Ongoing ACL research has demonstrated that the use of flexible nonparametric Bayesian models for learning models of uncertain environment can greatly improve planning performance.

UAV Mission Technologies: ACL has developed a novel hovering vehicle concept capable of agile, acrobatic maneuvers in cluttered indoor

spaces. The vehicle is a quadrotor whose rotor tilt angles can be actuated, enabling upside-down hovering flight with appropriate control algorithms. As part of research on long-duration UAV mission planning, ACL has also constructed an autonomous recharge platform, capable of autonomous battery replacement for small UAVs.

Information-Gathering Networks: Recent ACL research has addressed maximizing information gathering in complex dynamic environments, through the use of mobile sensing agents. The primary challenge in such planning is the computational complexity, due to both the large size of the information space and the cost of propagating sensing data into the future. ACL developed methodologies that correctly and efficiently quantify the value of information in large information spaces, such as a weather system, leading to a systematic architecture for mobile sensor network design. ACL researchers created communication cost efficient distributed fusion algorithms using decentralized metrics on value of information. Recently-developed algorithms embed information planning within RRTs to quickly identify safe information-gathering trajectories for teams of sensing agents, subject to arbitrary constraints and sensor models.

Multi-Agent Decision-Making: Markov Decision Processes are a natural framework for formulating many decision problems of interest; ACL has identified approximate solution techniques which can utilize this framework while overcoming the curse of dimensionality typically encountered for exact solutions. By exploiting flexible, kernel-based cost approximation architectures, ACL's Bellman Residual Minimization algorithm computes an approximate policy by minimizing the error incurred in solving Bellman's equation over sampled states. For online systems, ACL introduced incremental Feature Dependency Discovery (iFDD) algorithm that expands the representation in areas where the sampled Bellman error persist. iFDD has guaranteed rate and asymptotic convergence results and is computationally cheap, hence amenable to systems with restricted thinking time between actions. Finally, ACL has enabled fast,

real-time learning in combination with cooperative planning in uncertain and risky environments, while maintaining probabilistic safety guarantees for the overall system behavior.

ACL faculty are Jonathan How and Steven Hall.

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

AEROSPACE ROBOTICS AND EMBEDDED SYSTEMS

The Aerospace Robotics and Embedded Systems group's mission is the development of theoretical foundations and practical algorithms for real-time control of large-scale vehicle and mobile robot systems. Application examples range from UAVs and autonomous cars, to air traffic control, and urban mobility. The group researches advanced algorithmic approaches to control high-dimensional, fast, and uncertain dynamical systems subject to stringent safety requirements in a rapidly changing environment. An emphasis is placed on the development of rigorous analysis, synthesis, and verification tools to ensure the correctness of the design. The research approach combines expertise in control theory, robotics, optimization, queuing theory, and stochastic systems, with randomized and distributed algorithms, formal languages, machine learning, and game theory.

Current research areas include:

Real-time motion planning and control: The group is developing state-of-the art algorithms for real-time control of highly maneuverable aircraft, spacecraft, and ground vehicles. Focus areas include optimality and robustness, as well as provable safety and correctness with respect to temporal-logic specifications (e.g., rules of the road, rules of engagement). Current projects include high-speed flight in cluttered environments, and high-speed off-road driving.

Multi-agent systems: Large, heterogeneous groups of mobile vehicles, such as UAVs and UGVs, are increasingly used to address complex missions for many applications, ranging from national security to environmental monitoring. An additional emphasis in this work is

scalability: namely, our objective is not only the design of distributed algorithms to ensure provably efficient and safe execution of the assigned tasks, but also to understand exactly how the collective performance and implementation complexity scale as the group's size and composition change.

Transportation networks: Traffic congestion, and extreme sensitivity to, for example, environmental disruptions, is a well-known effect of increasing access to transportation. As infrastructure development saturates, new approaches are necessary to increase the safety, efficiency, and environmental sustainability of transportation networks. The group's research in this area concentrates on the exploitation of real-time information availability through wireless communications among vehicles, and with existing infrastructure, to achieve this goal.

ARES is directed by Emilio Frazzoli.

Visit the Aerospace Robotics and Embedded Systems group at <http://ares.lids.mit.edu>

THE AUTONOMOUS SYSTEMS LABORATORY

The Autonomous Systems Laboratory is a virtual lab led by Professors Brian Williams and Nicholas Roy. Williams' Model-based Embedded and Robotics (MERS) group and Roy's Robust Robotics Group are part of the Computer Science and Artificial Intelligence Lab. ASL work is focused on developing autonomous aerospace vehicles and robotic systems. ASL-developed systems are commanded at a high-level in terms of mission goals. The systems execute these missions robustly by constantly estimating their state relative to the world, and by continuously adapting their plan of action, based on engineering and world models.

Below are several recent demonstrations.

- » Operating autonomous vehicles to maximize utility in an uncertainty environment, while operating within accept-

able levels of risk. Autonomous underwater vehicles enable scientists to explore previously uncharted portions of the ocean by autonomously performing science missions of up to 20 hours in length without the need for human intervention. Performing these extended missions can be risky. Researchers have developed robust, chance-constraint planning algorithms that automatically navigate vehicles to achieve user specified science goals, while operating within risk levels specified by the users. (Video at <http://www.csail.mit.edu/videoarchive/research/robo/auv-planning>)

Another demonstration involves human-robot interaction between a robotic air taxi and a passenger. The task is for the autonomous vehicle to help the passenger rethink goals when they no longer can be met. Companies like the AeroAstro spinoff Terrafugia offer vehicles that can fly between local airports and can travel on local roads. To operate these innovative vehicles, one must be trained as a certified pilot, thus limiting the population that can benefit from this innovative concept. In collaboration with Boeing, MERS has demonstrated in simulation the concept of an autonomous personal air vehicle, in which the passenger interacts with the vehicle in the same manner that they interact today with a taxi driver. (Video at <http://www.csail.mit.edu/videoarchive/research/robo/personal-aerial-transportation>.)

- » A third demonstration involves human-robot interaction between an astronaut and the Athlete Lunar Rover. MERS has developed methods for controlling walking machines, guided by qualitative "snapshots" of walking gait patterns. These control systems achieve robust walking over difficult terrain by embodying many aspects of a human's ability to restore balance after stumbling, such as adjusting ankle support, moving free limbs, and adjusting foot placement. Members of the MERS group applied generalizations of these control concepts to control the JPL Athlete robot, a six-legged/

wheeled lunar rover that performs heavy lifting and manipulation tasks by using its legs as arms. (Video at <http://www.csail.mit.edu/videoarchive/research/robo/athlete-mers>.)

ASL faculty are Brian Williams and Nicholas Roy.

Visit *Model-based Embedded Systems* at mers.csail.mit.edu and the *Robust Robotics Group* at <http://groups.csail.mit.edu/rrg>

COMMUNICATIONS AND NETWORKING RESEARCH GROUP

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

The group is working on a wide range of projects in the area of communication networks and systems, with application to satellite, wireless, and optical systems. In recent years, the group has been developing efficient network control algorithms for heterogeneous wireless networks. Existing wireless networks are almost exclusively confined to single hop access, as provided by cellular telephony or wireless LANs. While multi-hop wireless networks can be deployed, current protocols typically result in extremely poor performance for even moderate sized networks. Wireless Mesh Networks have emerged as a solution for providing last-mile Internet access. However, hindering their success is our relative lack of understanding of how to effectively control wireless networks, especially in the

context of advanced physical layer models, realistic models for channel interference, distributed operations, and interface with the wired infrastructure (e.g., internet). CNRG is developing effective and practical network control algorithms that make efficient use of wireless resources through the joint design of topology adaptation, network layer routing, link layer scheduling, and physical layer power, channel, and rate control.

Robust network design is another exciting area of the group's recent pioneering research. In particular, the group is developing a new paradigm for the design of highly robust networks that can survive a massive disruption that may result from natural disasters or intentional attack. The work examines the impact of large-scale failures on network survivability and design, with a focus on interdependencies between different networked infrastructures, such as telecommunication networks, social networks, and the power grid. The group's research crosses disciplinary boundaries by combining techniques from network optimization, queueing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Eytan Modiano directs the Communications and Networking Research Group.

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

GAS TURBINE LABORATORY

The MIT Gas Turbine Laboratory has had a worldwide reputation for research and teaching at the forefront of gas turbine technology for more than 60 years. GTL's mission is to advance the state-of-the-art in fluid machinery for power and propulsion. The research is focused on advanced propulsion systems, energy conversion, and power, with activities in computational, theoretical, and experimental study of loss mechanisms and unsteady flows in fluid machinery, dynamic behavior and stability of compression systems, instrumentation and

diagnostics, advanced centrifugal compressors and pumps for energy conversion, gas turbine engine and fluid machinery noise reduction and aero-acoustics, novel aircraft, and propulsion system concepts for reduced environmental impact.

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

Faculty and research staff include: Fredric Ehrich, Alan Epstein (emeritus), Edward Greitzer, Claudio Lettieri, Jürg Schiffmann, Zoltan Spakovszky (director), Alejandra Uranga, and Choon Tan.

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

HUMANS AND AUTOMATION LABORATORY

Research in the Humans and Automation Laboratory focuses on the multifaceted interactions of human and computer decision-making in complex sociotechnical systems. With the explosion of automated technology, the need for humans as supervisors of complex automatic control systems has replaced the need for humans in direct manual control. A consequence of complex, highly automated domains in which the human decision-maker is more on-the-loop than in-the-loop is that the level of required cognition has moved from that of well-rehearsed skill execution and rule following to higher, more

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

Current research projects include investigation of human understanding of complex optimization algorithms and visualization of cost functions, human performance modeling with hidden Markov models, collaborative human-computer decision making in time-pressured scenarios (for both individuals and teams), human supervisory control of multiple unmanned vehicles, and designing displays that reduce training time. Lab equipment includes an experimental testbed for future command and control decision support systems intended to aid in the development of human-computer interface design recommendations for future unmanned vehicle systems. In addition, the lab hosts a state-of-the-art multi-workstation collaborative teaming operations center, as well as a mobile command and control experimental test bed mounted in a van awarded through the Office of Naval Research. Current research sponsors include the Office of Naval Research, the U.S. Army, Lincoln Laboratory, Boeing, the Air Force Research Laboratory, the Air Force Office of Scientific Research, Alstom, and the Nuclear Regulatory Commission.

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

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

INTERNATIONAL CENTER FOR AIR TRANSPORTATION

The International Center for Air Transportation undertakes research and educational programs that discover and disseminate the knowledge and tools underlying a global air transportation industry driven by technologies. Global information systems are central to the future operation of international air transportation. Modern

information technology systems of interest to ICAT include global communication and positioning; international air traffic management; scheduling, dispatch, and maintenance support; vehicle management; passenger information and communication; and real-time vehicle diagnostics.

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

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

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

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

The Laboratory for Information and Decision Systems is an interdepartmental research center committed to advancing research and education in the analytical information and decision sciences, specifically: systems and control, communications and networks, and inference and statistical data processing.

Dating to 1939, LIDS has been at the forefront of major methodological developments, relevant to diverse areas of national and worldwide importance, such as telecommunications, information technology, the automotive industry, energy, defense, and human health. Building on past innovation and bolstered by a collaborative atmosphere, LIDS members make breakthroughs that cut across traditional boundaries.

Members of the LIDS community share a common approach to solving problems and recognize the fundamental role that mathematics, physics, and computation play in their research. Their pursuits are strengthened by the laboratory's affiliations with colleagues across MIT and throughout the world, as well as with leading industrial and government organizations.

LIDS is based in MIT's Stata Center, a dynamic space that promotes a high level of interaction within the lab and with the larger MIT community. Currently, 17 faculty are affiliated with the laboratory, including Emilio Frazzoli, Jonathan How, Eytan Modiano, and Moe Win.

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

LEAN ADVANCEMENT INITIATIVE

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

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

tional outreach and training capabilities and includes more than 60 educational institutions around the world.

AeroAstro LAI participants include Deborah Nightingale (co-director), Earll Murman, and Annalisa Weigel.

Visit the Lean Advancement Initiative at <http://lean.mit.edu>

THE LEARNING LABORATORY

The AeroAstro Learning Laboratory, located in Building 33, promotes student learning by providing an environment for hands-on activities that span our conceive-design-implement-operate educational paradigm.

The Learning Lab comprises four main areas:

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

- » The Concept Forum — a multipurpose room for meetings, presentations, lectures, video conferences and collaboration, distance learning, and informal social functions. In the Forum, students work together to develop multidisciplinary concepts, and learn about program reviews and management.
- » Al Shaw Student Lounge — a large, open space for social interaction and operations.

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

Gerhard Neumann Hangar. The Gerhard Neumann Hangar is a high bay space with an arching roof. This space lets students work on large-scale projects that take considerable floor and table space. Typical of these projects are planetary rovers, autonomous vehicles, and re-entry impact experiments. The structure also houses low-speed and supersonic wind tunnels. A balcony-like mezzanine level is used for multi-semester engineering projects, such as the experimental three-term senior capstone course, and is outfitted with a number of flight simulator computer stations.

Digital Design Studio. The Digital Design Studio, located on the second floor, is a large room with multiple computer stations arranged around reconfigurable conference tables. Here, students conduct engineering evaluations and design work, and exchange computerized databases as system and subsystem trades are conducted during the development cycle. The room is equipped with information technologies that facilitate teaching and learning in a team-based environment. Adjacent and networked to the main Design Studio are two smaller design rooms: the AA Department Design Room, and the Arthur W. Vogeley Design Room. These rooms are reserved for the use of individual design teams and for record storage. The department's IT systems administrator is positioned for convenient assistance in an office adjacent to the Design Center.

Some of the projects undertaken by students in the Learning Lab during the past year include a planetary rover with wheels that self-adjust for different surfaces, construction of an aircraft for the AIAA Design/Build/Fly competition, and development of the Locust miniature UAV.

MAN VEHICLE LABORATORY

The Man Vehicle Laboratory addresses human-vehicle and human-robotic system safety and effectiveness by improving understanding of human physiological and cognitive capabilities. MVL develops countermeasures and display designs to aid pilots, astronauts, and others. Research is interdisciplinary and uses techniques from manual and supervisory control, signal processing, estimation, robotics, sensory-motor physiology, sensory and cognitive psychology, biomechanics, human factors engineering, artificial intelligence, and biostatistics. MVL has flown experiments on Space Shuttle missions, the Mir Space Station, and on many parabolic flights, and developed experiments for the International Space Station.

MVL has five faculty and 20 affiliated graduate students. Research sponsors include NASA, the National Space Biomedical Research Institute, the Office of Naval Research, the FAA and Federal Railroad Administration, the Center for Integration of Medicine and Innovative Technology, the Deshpande Center, and the MIT Portugal Program. Space projects focus on advanced space suit design and dynamics of astronaut motion, adaptation to rotating artificial gravity, mathematical models for human spatial disorientation accident analysis, artificial intelligence, and space telerobotics training. New major projects include a collaborative study with Draper laboratory on manual and supervisory control of lunar/planetary landings, and a study of fatigue effects on space teleoperation performance, in collaboration with colleagues at the Brigham and Women's Hospital. Non-aerospace projects include performance and fatigue effects in locomotive engineers and advanced helmet designs for brain protection in sports and against explosive blasts. The laboratory also collaborates with the Volpe Transportation Research Center and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

MVL faculty include Charles Oman (director), Jeffrey Hoffman, Dava Newman, Laurence Young, and Julie Shah. They teach subjects in human factors engineering, space systems engineering, real-time systems and software, space policy, flight simulation, space physi-

ology, aerospace biomedical engineering, the physiology of human spatial orientation, and leadership. The MVL also serves as the office of the Director for the NSBRI-sponsored HST Graduate Program in Bioastronautics (Young), the Massachusetts Space Grant Consortium (Hoffman), NSBRI Sensory-Motor Adaptation Team (Oman), the MIT-Volpe Program in Transportation Human Factors (Oman), and the MIT Portugal Program's Bioengineering Systems focus area (Newman).

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

NECSTLAB

The necstlab (pronounced "next lab") research group explores new concepts in engineered materials and structures. The group's mission is to lead the advancement and application of new knowledge at the forefront of materials and structures understanding, with research contributions in both science and engineering. Applications of interest include enhanced (aerospace) advanced composites, multifunctional attributes of structures such as damage sensing, and also microfabricated (MEMS) topics. A significant effort over the past decade has been to use nanoscale materials to enhance performance of advanced aerospace materials and their structures through the industry supported NECST Consortium.

The necstlab group has interests that span from fundamental materials synthesis questions to structural applications of both hybrid and traditional materials. This includes long-standing projects in MEMS and now bioNEMS/MEMS. While not all-encompassing, much of the group's work supports the efforts of the NECST Consortium, an aerospace industry-supported research initiative that develops the underlying understanding to create enhanced-performance advanced composites using nanotechnology. Beyond the NECST Consortium Members, necstlab research is supported by industry, AFOSR, ARO, NASA, NIST, NSF, ONR, and others.

The necstlab maintains collaborations around the MIT campus, particularly with faculty in the Mechanical Engineering, Materials Science and Engineering, and Chemical Engineering departments, and MIT

labs and centers including the Institute for Soldier Nanotechnologies, Materials Processing Center, Center for Materials Science and Engineering, and the Microsystems Technology Laboratory, as well as Harvard's Center for Nanoscale Systems. Important to the contributions of the necstlab are collaborations with leading research groups from around the world through formal and informal collaborations.

Example past and current research projects include:

- » BioNEMS materials design and implementation in microfluidics
- » buckling mechanics
- » carbon nanostructure synthesis from non-traditional catalysts
- » continuous growth of aligned carbon nanotubes
- » electroactive nanoengineered actuator/sensor architectures focusing on ion transport
- » nanoengineered (hybrid) composite architectures for laminate-level mechanical performance improvement
- » multifunctional properties including damage sensing and detection
- » manufacturing
- » polymer nanocomposite mechanics and electrical and thermal transport
- » Si MEMS devices including piezoelectric energy harvesters, microfabricated solid oxide fuel cells, stress characterization, and 3D MEMS
- » VACNT characterization and physical properties

necstlab faculty include Brian L. Wardle (director), John Dugundji (emeritus), and visitors Antonio Miravete and Desiree Plata

Visit necstlab at

<http://web.mit.edu/dept/aeroastro/labs/necstlab>

THE PARTNERSHIP FOR AIR TRANSPORTATION NOISE AND EMISSIONS REDUCTION

The Partnership for Air Transportation Noise and Emissions Reduction is an MIT-led FAA Center of Excellence sponsored by the FAA, NASA, Transport Canada, the US Department of Defense, and the Environmental Protection Agency. PARTNER research addresses environmental challenges facing aviation through analyzing community noise and emission impacts on climate and air quality. PARTNER also studies a range of environmental impact potential mitigation options including aircraft technologies, fuels, operational procedures, and policies. PARTNER combines the talents of 12 universities, five government agencies, and more than 50 advisory board members, the latter spanning a range of interests from local government, to industry, to citizens' community groups.

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

Other PARTNER initiatives in which MIT participates include estimating the lifecycle impacts of alternative fuels for aircraft, studies of aircraft particulate matter microphysics and chemistry, and economic analysis of policies. PARTNER's most recent reports include "Environmental Cost-Benefit Analysis of Ultra Low Sulfur Jet Fuel," and "CO₂ Emission Metrics for Commercial Aircraft Certification: A National Airspace System Perspective." In addition, MIT PARTNER researchers have contributed to recently published reports and papers on such topics as traditional and alternative fuel use, aircraft emissions, and emissions trading. PARTNER reports may be accessed at <http://web.mit.edu/aeroastro/partner/reports>

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

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

SPACE PROPULSION LABORATORY

The Space Propulsion Laboratory studies and develops systems for increasing performance and reducing costs of space propulsion and related technologies. A major area of interest to the lab is electric propulsion in which electrical, rather than chemical, energy propels spacecraft. The benefits are numerous, hence the reason electric propulsion systems are increasingly applied to communication satellites and scientific space missions. These efficient engines allow detailed exploration of the universe's structure, increase the lifetime of commercial payloads, and look for signs of life in far away places. Areas of research include plasma thrusters and plumes and their interaction with spacecraft; numerical and experimental models of magnetic cusped thrusters; and space electrodynamic tethers, including their use as antennas for launching electromagnetic waves to remove high-energy particles from earth's Van Allen radiation belts. SPL students work on ultra-fast (nanosecond) high voltage discharges to trigger combustion reactions and eventually reduce aircraft engine pollution.

SPL also has a significant role in designing and building micropropulsion electro-spray thrusters. In addition to providing efficient propulsion for very small satellites in the 1 kg category (such as CubeSats), such engines will enable distributed propulsion for the control of large space structures, like deformable mirrors and apertures. SPL facilities include a supercomputer cluster where plasma and molecular dynamics codes are routinely executed and a state-

of-the-art laboratory including three vacuum chambers, clean room environment benches, electron microscope and electronic diagnostic tools to support ongoing research efforts.

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

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

SPACE SYSTEMS LABORATORY

Space Systems Laboratory research contributes to space exploration and development. SSL's mission is to explore innovative space systems concepts while training researchers to be conversant in this field. The major programs include systems analysis studies and tool development, precision optical systems for space telescopes, microgravity experiments conducted aboard the International Space Station, and leading the AeroAstro efforts on student-built small satellites. Research encompasses an array of topics that comprise a majority of space systems: systems architecting, dynamics and control, active structural control, thermal analysis, space power and propulsion, microelectromechanical systems, modular space systems design, micro-satellite design, real-time embedded systems, and software development.

Several SSL initiatives study the development of formation flight technology. The Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) facility is used to develop proximity satellite operations such as inspection, cluster aggregation, collision avoidance and docking. The SPHERES facility consists of three satellites 20 centimeters in diameter that have flown inside the International Space Station since May 2006. In 2009, we expanded the uses of SPHERES to include Science, Technology, Engineering, and Mathematics (STEM) education outreach. In the fall of 2009 we began an exciting program called Zero Robotics to engage high school

students in a competition aboard the ISS using SPHERES (<http://www.zerorobotics.org>). In December 2010 ten students from two Idaho schools came to MIT and saw their algorithms compete against each other in a live feed from the ISS. Since then, Zero Robotics has been expanded to include middle school programs as well as a competition in Europe. In 2012, more than 130 high schools nationwide and 20 schools in Europe competed. Also in 2012, the SPHERES facility on ISS is being expanded to include vision-based navigation and magnetic control of satellite formations.

The SSL performs research in space instrumentation and optics (<http://web.mit.edu/cahoylab>). The Wavefront Control Laboratory develops instruments and algorithms that allow us to explore both our Earth and other worlds from space. WCL demonstrates wavefront control using MEMS deformable mirrors, Shack-Hartmann wavefront sensors, and liquid crystal atmospheric turbulence simulators. Wavefront control systems are needed for applications such as space-based direct imaging of exoplanets (planets around other stars), laser communication systems (to improve bit error rate), and imaging systems (to correct for atmospheric turbulence or aberrations caused by the imaging system optics). WCL also uses radio-frequency waves to study the atmosphere and ionosphere of Earth and other Solar System planets with a technique called radio occultation. In addition, WCL has projects with industry investigate the connection between on-orbit component anomalies and space weather for commercial geostationary communications spacecraft. WCL also supports analyses of radio science gravity field data from exploratory spacecraft, such as GRAIL.

The SSL is also developing nano-satellites to advance and mature innovative instrumentation and spacecraft bus designs for remote sensing missions. Examples include a dual-spinning 3U CubeSat to host a passive microwave radiometer (Microsized Microwave Atmospheric Satellite, MicroMAS, in collaboration with MIT Lincoln Laboratory), a cluster flight of three 3U CubeSats equipped with electropray microthrusters (in collaboration with MIT AeroAstro's

Space Propulsion Lab and Aurora Flight Sciences), and a 3U Cubesat for transit detection of Earth-like planets around the nearest, brightest stars (in collaboration with MIT's Earth and Planetary Sciences Department and Draper Laboratory). Also under development are the TERSat satellite (Trapped Energetic Radiation Satellite) for precipitation of energetic particles from the radiation belts under the Air Force's University Nano-satellite Program (in collaboration with MIT AeroAstro's Space Propulsion Laboratory) and the REXIS (REgolith X-ray Imaging Spectrometer) instrument on NASA's OSIRIS-Rex asteroid sample return mission launching in 2016.

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

SSL personnel include David W. Miller (director), Kerri Cahoy, Olivier de Weck, Jeffrey Hoffman, Manuel Martinez-Sanchez, Paulo Lozano, Alvar Saenz-Otero, Rebecca Masterson, Paul Bauer (research specialist), Jori Barabino (fiscal officer), and Marilyn E. Good (administrative assistant).

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

SYSTEM SAFETY RESEARCH LAB

The increasingly complex systems we are building today enable us to accomplish tasks that were previously difficult or impossible. At the same time, they have changed the nature of accidents and increased the potential to harm not only life today but also future generations. Traditional system safety engineering approaches, which started in the missile defense systems of the 1950s, are challenged by the introduction of new technology and the increasing complexity of the

systems we are attempting to build. Software is changing the causes of accidents and the humans operating these systems have a much more difficult job than simply following pre-defined procedures. We can no longer effectively separate engineering design from human factors and from the social and organizational system in which our systems are designed and operated.

The Laboratory for Systems Safety Research's goal is to create tools and processes that allow us to engineer a safer world. Engineering safer systems requires multidisciplinary and collaborative research based on sound system engineering principles, that is, it requires a holistic systems approach. LSSR has participants from multiple engineering disciplines and MIT schools as well as collaborators at other universities and in other countries. Students are working on safety in aviation (aircraft and air transportation systems), spacecraft, medical devices and healthcare, automobiles, railroads, nuclear power, defense systems, energy, and large manufacturing/process facilities. Cross-discipline topics include:

- » hazard analysis
- » accident causality analysis and accident investigation
- » safety-guided design
- » human factors and safety
- » integrating safety into the system engineering process
- » identifying leading indicators of increasing risk
- » certification, regulation, and standards
- » the role of culture, social, and legal systems on safety
- » managing and operating safety-critical systems

The System Safety Research Lab is directed by Nancy Leveson.

TECHNOLOGY LABORATORY FOR ADVANCED MATERIALS AND STRUCTURES

A dedicated and multidisciplinary group of researchers constitute the Technology Laboratory for Advanced Materials and Structures. They work cooperatively to advance the knowledge base and understanding that will help facilitate and accelerate advanced materials systems development and use in various advanced structural applications and devices.

TELAMS has broadened its interests from a strong historical background in composite materials, and this is reflected in the name change from the former Technology Laboratory for Advanced Composites. Thus, the research interests and ongoing work in the laboratory represent a diverse and growing set of areas and associations. Areas of interest include:

- » composite tubular structural and laminate failures
- » MEMS-scale mechanical energy harvesting modeling, design, and testing
- » MEMS device modeling and testing, including bioNEMS/MEMS
- » structural health monitoring system development and durability assessment
- » thermostructural design, manufacture, and testing of composite thin films and associated fundamental mechanical and microstructural characterization
- » continued efforts on addressing the roles of lengthscale in the failure of composite structures
- » numerical and analytical solid modeling to inform, and be informed by, experiments
- » continued engagement in the overall issues of the design of composite structures with a focus on failure and durability, particularly within the context of safety

In supporting this work, TELAMS has complete facilities for the fabrication of structural specimens such as coupons, shells, shafts, stiffened panels, and pressurized cylinders made of composites, active, and other materials. TELAMS testing capabilities include a battery of servohydraulic machines for cyclic and static testing, a unit for the catastrophic burst testing of pressure vessels, and an impact testing facility. TELAMS maintains capabilities for environmental conditioning, testing at low and high temperature, and in hostile and other controlled environments. There are facilities for microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization. This includes ties to ability for computer microtomography.

With its linked and coordinated efforts, both internal and external, the laboratory continues its commitment to leadership in the advancement of the knowledge and capabilities of the materials and structures community through education of students, original research, and interactions with the community. There has been a broadening of this commitment consistent with the broadening of the interest areas in the laboratory. In all these efforts, the laboratory and its members continue their extensive collaborations with industry, government organizations, other academic institutions, and other groups and faculty within the MIT community.

TELAMS faculty include Paul A. Lagacé, John Dugundji (emeritus), and visitor Antonio Miravete.

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

WIRELESS COMMUNICATION AND NETWORK SCIENCES GROUP

The Wireless Communication and Network Sciences Group is involved in multidisciplinary research that encompasses developing fundamental theories, designing algorithms, and conducting experiments for a broad range of real-world problems. Its current research topics include location-aware networks, network synchronization, aggregate interference, intrinsically-secure networks, time-varying channels, multiple antenna systems, ultra-wide bandwidth systems, optical transmission systems, and space communications systems. Details of a few specific projects are given below.

The group is working on location-aware networks in GPS-denied environments, which provide highly accurate and robust positioning capabilities for military and commercial aerospace networks. It has developed a foundation for the design and analysis of large-scale location-aware networks from the perspective of theory, algorithms, and experimentation. This includes derivation of performance bounds for cooperative localization, development of a geometric interpretation for these bounds, and the design of practical, near-optimal cooperative localization algorithms. It is currently validating the algorithms in a realistic network environment through experimentation in the lab.

The lab has been engaged in the development of a state-of-the-art apparatus that enables automated channel measurements. The apparatus makes use of a vector network analyzer and two vertically polarized, omni-directional wideband antennas to measure wireless channels over a range of 2–18 GHz. It is unique in that extremely wide bandwidth data, more than twice the bandwidth of conventional ultra-wideband systems, can be captured with high-precision positioning capabilities. Data collected with this apparatus facilitates the efficient and accurate experimental validation of proposed theories and enables the development of realistic wideband channel models. Work is underway to analyze the vast amounts of data collected during an extensive measurement campaign that was completed in early 2009.

Lab students are also investigating physical-layer security in large-scale wireless networks. Such security schemes will play increasingly important roles in new paradigms for guidance, navigation, and control of unmanned aerial vehicle networks. The framework they have developed introduces the notion of a secure communications graph, which captures the information-theoretically secure links that can be established in a wireless network. They have characterized the s-graph in terms of local and global connectivity, as well as the secrecy capacity of connections. They also proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and sectorized transmission. Lastly, they analyzed the capability for secure communication in the presence of colluding eavesdroppers.

To advocate outreach and diversity, the group is committed to attracting undergraduates and underrepresented minorities, giving them exposure to theoretical and experimental research at all levels. For example, the group has a strong track record for hosting students from both the Undergraduate Research Opportunities Program and the MIT Summer Research Program (MSRP). Professor Win maintains dynamic collaborations and partnerships with academia and industry, including the University of Bologna and Ferrara in Italy, University of Lund in Sweden, University of Oulu in Finland, National University of Singapore, Nanyang Technological University in Singapore, Draper Laboratory, the Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Moe Win directs the Wireless Communication and Network Sciences Group.

Visit the *Wireless Communication and Network Sciences Group* at <http://wgroup.lids.mit.edu>

WRIGHT BROTHERS WIND TUNNEL

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

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