Department of Aeronautics and Astronautics

MIT's Department of Aeronautics and Astronautics (AeroAstro) is one of America's oldest and most celebrated aerospace engineering departments, with undergraduate and graduate programs consistently ranked among the very best by *U.S. News & World Report*. Although the department remains focused on aeronautics and astronautics, the faculty is also engaged in research in a number of overlapping cross-disciplinary areas, with a significant presence that belies its medium size (approximately 250 graduate students, 150 undergraduates, and 35 faculty members).

A department centered around a dynamic industry, AeroAstro has committed to review and update its strategic plan with the goal of developing a guiding strategy for the upcoming decade. As part of this exercise, more than 60 aerospace leaders in industry, government, and academia were interviewed. The department also reached out to alumni (of more than 2,000 potential interviewees, more than 300 responded to our request), and spoke to Institute leadership. There was general consensus that department activities are aimed in the right direction. At the same time, there are exciting strategic opportunities, particularly in the areas of air transportation, autonomous aerospace systems, small satellites, and engineering education that are deserving of special effort and attention. In the coming months, the department plans to flesh out and implement actions to embrace these opportunities. As always, AeroAstro will approach these challenges by building on the individual strengths of its faculty and by collaborating with its colleagues inside and outside MIT.

Mission and Strategy

AeroAstro's mission is to prepare engineers for success and leadership in the conception, design, implementation, and operation of high-performance aerospace and related engineering systems. The department is committed to excellence and to the creation, development, and application of the technologies critical to aerospace vehicle and information engineering, and to the architecture and engineering of complex high-performance systems.

Our strategy has the following elements:

1. We are building a stronger faculty by hiring for excellence, mentoring, and promoting collaboration.
2. We are enhancing excellence in graduate and undergraduate education by reinvigorating our commitment to the development, assessment, and continuous improvement of our pedagogy and of our student learning.
3. We are improving our physical space by enhancing maintenance procedures and investing in space renovations.

Promoting Faculty Excellence

The AeroAstro faculty includes Hamsa Balakrishnan, Steven Barrett, Edward Crawley (0.5 full-time equivalent [FTE], dual appointment with Engineering Systems Division, on leave while president of the Skolkovo Institute of Science and Technology), Kerri Cahoy, Mary Cummings, David Darmofal, Olivier de Weck (0.5 FTE, dual appointment with Engineering Systems Division), Mark Drela, Emilio Frazzoli, Edward Greitzer, Steven Hall, R. John Hansman, Wesley Harris (in full-time administrative role as associate provost for faculty equity), Daniel Hastings (0.5 FTE, dual appointment with Engineering Systems Division, in full-time administrative role as dean of undergraduate education), Jonathan How, Sertac Karaman (joined the department on October 1, 2012), Paul Lagacé, Nancy Leveson (0.5 FTE, dual appointment with Engineering Systems Division), Paulo Lozano, Manuel Martínez-Sánchez, Youssef Marzouk, David W. Miller, David Mindell (0.5 FTE, dual appointment with Science, Technology, and Society in the School of Humanities, Arts, and Social Sciences), Eytan Modiano, Dava Newman (0.5 FTE, dual appointment with Engineering Systems Division), Jaime Peraire, Raul Radovitzky, Nicholas Roy, Julie Shah, Zoltan Spakovszky, Ian Waitz (in full-time administrative role as dean of the school of engineering), Qiqi Wang, Brian Wardle, Sheila Widnall, Karen Willcox, Brian Williams, Moe Win, and Laurence Young. Professor Peraire is department head; Professor Willcox is associate department head

Department faculty members meet on a weekly basis, providing a forum for research presentations, departmental updates, and general discussion. During the academic year, the department welcomes individuals from other units across campus to present at these meetings. Outside presentations during AY2013 included "Introduction to the eFPR" and "Update on *MITx*," among others. These weekly meetings are a mainstay of department life and allow faculty to stay connected to one another and to the larger Institute.

Junior faculty also enjoy periodic meetings with department leadership, during which topics unique to this cohort are discussed. Professors Peraire and Willcox both recognize the importance of appropriate mentoring for the department's junior faculty, and encourage open lines of communication between leadership and all faculty members.

Promotions

- Olivier de Weck was promoted to full professor, effective July 1, 2013.
- Emilio Frazzoli was promoted to full professor, effective July 1, 2013.
- Paulo Lozano was promoted to associate professor with tenure, effective July 1, 2013.

Recognition

- Professor Hansman was elected to the National Academy of Engineering for "development of aviation display and alerting systems for air safety."
- Professor Young was awarded the National Space Biomedical Research Institute Pioneer Award for "efforts and accomplishments that blazed trails on behalf of the Institute, NASA, and the space biomedical community."

- Professor Jaime Peraire was named an American Institute of Aeronautics and Astronautics (AIAA) Fellow.
- Professor David Mindell was awarded the AIAA Gardner Lasser Aerospace Literature Award for his book *Digital Apollo*.
- The Polytechnic University of Madrid conferred a Doctor Honoris Causa upon professor Manuel Martínez-Sánchez.
- The American Society for Composites presented professor Paul Lagacé with its 2012 Outstanding Research Award in Composites.
- Professor Hamsa Balakrishnan and professor Jeffrey Hoffman were named AIAA Associate Fellows.
- Professor Steven Hall was elected MIT faculty chair for the period beginning July 1, 2013, serving as faculty chair-elect in the interim.
- AeroAstro professor and associate provost for faculty equity Wesley Harris was selected to receive the National Organization for the Professional Advancement of Black Chemists and Chemical Engineers' President's Award.
- Undergraduate dean Daniel Hastings was appointed the Green education professor of aeronautics and astronautics and engineering systems.
- Professor Kerri Cahoy was named MIT's outstanding mentor in the Undergraduate Research Opportunity Program (UROP) AY2013 for "exceptional guidance and teaching in a research setting."
- Professor Sheila Widnall was honored with the AIAA Undergraduate Advising Award, given by the AIAA student chapter, for "demonstrating excellence in serving as an academic or 16.621/16.622 advisor and having made a real positive impact on a student's time in the AeroAstro Department."
- Professor David Darmofal was honored with the AIAA Undergraduate Teaching Award, given by the AIAA student chapter, for "exemplifying the role of a great teacher."
- Professor Jaime Peraire was awarded the SEMNI Prize by the Spanish Society for Numerical Methods in Engineering.

Promoting Excellence in Graduate Education

AeroAstro received 545 applications for admission to its graduate programs, admitting 86 applicants (admission rate of 16 percent). Of the 86 admitted, 60 students enrolled, for a yield of 70 percent.

The department's graduate program was again ranked #1 in the country by *U.S. News and World Report*—a ranking shared with the California Institute of Technology (Caltech).

Continuing a tradition of formal end-of-semester progress reviews, department faculty regularly meet with all graduate students in an effort to enhance professional development, feedback, and mentoring. Professors Peraire and Willcox also meet regularly with the graduate student body, engaging in a dialogue designed to promote feedback and develop a stronger sense of involvement in department business.

Recognition

- Sunny Wicks was awarded the AIAA's Lockheed Martin Award for Best Structures paper: "Interlaminar Fracture Toughness of Laminated Woven Composites Reinforced with Aligned Nanoscale Fibers: Mechanisms at the Macro, Micro, and Nano Scales."
- Chelsea He, Annie Marinan, Whitney Lohmeyer, Emily Clements, Sunny Wicks, Sreeja Nag, and Allie Anderson were named "Graduate Women of Excellence" by the Office of the Dean for Graduate Education for "their leadership and service contributions at the Institute, their dedication to mentoring and their drive to make changes to improve student experience." Also honored was the Women's Graduate Association of Aeronautics and Astronautics (WGA^3).

Graduate student Chelsea He demonstrates a mini wind tunnel at the American Association for the Advancement of Science Family Day at Boston's Hynes Convention Center. A number of AeroAstro students volunteered for the event, working with hundreds of families to build paper planes, fly Alka-Seltzer rockets, learn about UAVs, and much more. Outreach to young people is of primary importance to the AeroAstro Department.

- Tony Tao, AeroAstro graduate student and teaching assistant, was awarded MIT's 2013 Goodwin Medal for "conspicuously effective teaching" by a graduate student.
- Farah Alibay and Tony Tao were both recognized with AeroAstro Graduate Teaching Assistantship Awards for "demonstrating conspicuous dedication and skill in helping fulfill an undergraduate or graduate subject's educational objectives."
- Christopher Gilmore was awarded the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence Student of the Year Award.
- The Rene H. Miller Prize in Systems Engineering, which is given to a student "who has done the best piece of work in systems engineering in the AeroAstro department," was awarded to Alexander James Buck and Austin Kyle Nicholas.
- The AeroAstro AIAA Teaching Assistantship Award was given to Sarah K. Ferguson "for outstanding commitment to pedagogy, inspiration, and superior contributions to the 16.07 class."

Promoting Excellence in Undergraduate Education

In 2012–2013, the 16-1 and 16-2 degrees were combined into a single aerospace engineering degree program (Course 16 – Aerospace Engineering). Because of the emphasis on aerospace information technology in the preparation of all aerospace engineers, the faculty agreed that there was no longer a need for a separate degree program. The combined program retains a deep emphasis on the fundamentals and provides strong integration within the overarching conceive, design, implement, operate (CDIO) learning context.

The department was and remains strongly committed to promoting undergraduate research, hiring a number of students through UROP. In AY2013, AeroAstro hired 202 UROP students, of which 25 percent were freshmen. During summer 2013, 30 of the department's 67 UROP students (45 percent) were rising sophomores.

The department continues to require reflective memos of all undergraduate instructors as a means for promoting continuous improvement in faculty teaching performance.

Recognition

- Lockheed Martin Prize for Excellence in Systems Engineering Teamwork: the Design/Build/Fly team of Ivan Amador '14, Rebecca B. Colby '13, Casey L. Denham '15, Elizabeth A. Jones '14, Gregory D. Kravit '15, Giulia B. Pantalone '13, Samuel L. Range '13, Daniel J. Rankin '13, Margaret J. Reagan '16, Joseph M. Salinas '13, Jedediah Storey '13, Arshia S. Surti '15, Tony Tao G, Joseph Marcel R. Williams '14.
- Apollo Program Prize given to an AeroAstro student who conducts the best undergraduate research project on the topic of humans in space: Edward W. Obropta '13.
- Leaders for Manufacturing Undergraduate Prize given to a student team that has demonstrated excellence, innovation, or both, in addressing the interaction between manufacturing and engineering during the execution of their project: Andras L. Kiss '13 and Jay R. Pothula '13.
- United Technologies Corporation Prize awarded to an AeroAstro student for outstanding achievement in the design, construction, execution, and reporting of an undergraduate experimental project: James E. Byron '13 and Peter Florin '13.
- Admiral Luis De Florez Prize, awarded for "original thinking or ingenuity": Samuel L. Range '13.
- James Means Award for Excellence in Flight Vehicle Engineering: Elizabeth A. Jones '14.
- James Means Award for Excellence in Space Systems Engineering: Brian G. Coffee '13. Also awarded to Leonard I. Tampkins '13.
- Thomas B. Sheridan Award, given to an AeroAstro or Mechanical Engineering undergraduate student whose research or design project best exemplifies creativity or improvement in human-machine integration or cooperation: Elizabeth D'Arienzo '13 and James N. Wiken '13.

- Henry Webb Salisbury Award, given in memory of Henry Salisbury to a graduating senior who has achieved superior academic performance in the Course XVI Undergraduate Program: Andras L. Kiss ’13 and Harriet Li ’13.
- AeroAstro Undergraduate Teaching Assistantship Award, given to an undergraduate student who has demonstrated conspicuous dedication and skill in helping fulfill an undergraduate subject’s educational objectives: Brian G. Coffee ’13 and James N. Wiken ’13.

Improving AeroAstro’s Physical Space

The department’s space committee has been actively trying to manage and improve the quality of its space. It has initiated new protocols for reporting problems and maintenance issues. Furniture and audio-visual equipment, as well as some common areas and classrooms, have been upgraded. LED screens have been installed in several locations in the department to keep the community informed of the latest news and to showcase research.

The department continues to struggle with its physical plant. Because of its age and condition, much of the research space in the department is considered sub-par, placing AeroAstro at a competitive disadvantage. This is especially worrisome given the construction of new, world-class facilities at Stanford University and Caltech, AeroAstro’s closest rivals for graduate students and faculty.

As reported by the 2011 Corporation Visiting Committee, “It has become crystal clear that upgrading of research space has risen to the top of the list of priorities … the quality of space is simply deplorable. The equipment supporting the Gas Turbine Laboratory and Wright Brothers Wind Tunnel is ancient … urgently needs to be upgraded.”

The Wright Brothers Wind Tunnel, now 75 years old, is especially problematic. Used by every student who matriculates in the department, the iconic structure is often down for repairs, interfering not only with research but also education. Renovations must be a department priority to put both our educational and research missions on track.

Student offices are another area of departmental concern. Many of these spaces lack windows and have only cinder-block walls. Additionally, occupants have no real ability to control environmental temperature. It will require considerable effort to improve these spaces. Infrastructure generally, including bathrooms and accessibility for persons with disabilities in Building 31, is in dire need of upgrade.

Resource Development

The department has been allocated a resource development officer (0.5 FTE, shared with Biological Engineering) to increase philanthropic support for the faculty, students, and research projects within AeroAstro. Hired mid-year, Mark Veligor works closely with MIT fundraisers to promote AeroAstro initiatives with currently engaged prospects and to foster new relationships with alumni, parents, and friends who are interested in supporting the department.

In June, Professor Peraire spoke at intimate resource development events in Washington, DC. Hosted by Pierre Chao and attended by development officers Margaret Dimock and Mark Veligor. Guests included David and Lucia Bacon, Michael Dyment, Dr. Mark Epstein, Amoretta Hoeber, Andrew Good, Joseph Martore, David Baggett, Dr. Gail Marcus, Barbara Ostrom, and Anne Street.

Outreach

Professors Karen Willcox and Jeff Hoffman, along with members of the department staff and student body, hosted the department's first Freshman Pre-Orientation Program (FPOP)—"Discover Aerospace"—in August 2012. Attended by 30 freshmen, the four-day event was a rousing success. The students engaged in hands-on design and build activities, attended a planetarium show at the Museum of Science, and were given a sneak preview of life in the department. FPOP proved to be an exciting time for the students and a wonderful opportunity for the department to connect, inspire, and recruit. As we look to AY2014, we are delighted to report that 13 of the 30 students who participated in "Discover Aerospace" (43 percent) have declared AeroAstro as their major!

Several Space Systems Laboratory (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 (ISS) since May 2006. In 2009, the SSL expanded the uses of SPHERES to include science, technology, engineering, and mathematics (STEM) program outreach through an exciting program called Zero Robotics, which engages high-school students in a competition aboard the ISS using SPHERES (http://www.zerorobotics.org/). In December 2010, 10 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, 96 teams from the United States and 47 teams from Europe competed.

Aboard the International Space Station, astronaut Tom Marshburn works with an MIT Space Systems Lab SPHERES micro satellite. The visually enabled SPHERE is the red object on the lef—it's scrutinizing a target SPHERE that Marshburn's holding.

The department held its fifth Women in Aerospace Symposium (WIA) in April 2013. A now annual tradition, the event provides the department a unique opportunity to foster a network among top women doctoral students in aerospace. Bonnie Dunbar, former NASA astronaut and past president of the Museum of Flight, was the 2013 keynote speaker. Department guests included women from Princeton University, University of Colorado, University of Toronto, Cornell University, Stanford University, Caltech, Pennsylvania State University, and Harvard University. Although the two-day symposium was cut short by the citywide lockdown on April 19, 2013 (following the murder of MIT police officer Sean Collier), the department's guests persevered, holding a mini-symposium at their hotel.

Our fifth Women in Aerospace conference was held in April. The series of presentations by top women aerospace doctoral students from around the United States fosters networking and collegiality.

In updating the WIA alumnae list, the department was delighted to find that the majority of the women who have participated in the symposia have gone on to work in the aerospace field; many hold positions in academia.

Departmental Awards

- Sophia Hasenfus was the recipient of the Wings Award, established to recognize an individual support staff member in AeroAstro for excellence.
- Jennifer Craig (individual), comparative media studies/writing lecturer assigned to AeroAstro, and fiscal officers Ping Lee, Jennifer Leith, Suxin Hu, and Jori Barabino (group), received the Spirit of XVI Award, a recognition given to an individual or team in AeroAstro whose work, commitment, and enthusiasm contribute significantly to the achievement of the mission of the department.
- The Vickie Kerrebrock Award, given in recognition of students, staff, faculty or others (either individually or as members of a group) who have made significant contributions to building a sense of community was given to Manuel Martínez-Sánchez.

A Remarkable Year

Former NASA astronaut and moonwalker David Scott visited campus on behalf of the Astronaut Scholarship Foundation, presenting AeroAstro senior Mark Van de Loo with a scholarship check on behalf of the foundation.

Members of the NASA Jet Propulsion Laboratory's Mars Science Laboratory "Curiosity Dream Team," including AeroAstro alumni Bobak Ferdowsi and Allen Chen and former member of AeroAstro's Space Systems Laboratory Steven Sell, presented to a group of more than 150 students, faculty, and staff.

In June 2013, the department co-hosted the 9th International CDIO Conference.

Carlos Castillo-Chávez, an Arizona State University (ASU) professor, served as the Martin Luther King Visiting Professor. Professor Castillo-Chávez is founding director of ASU's Mathematical, Computational, and Modeling Sciences Center and its Mathematical and Theoretical Biology Institute.

Celebrating the Curiosity Mars rover's successful landing and initial operation, AeroAstro invited MIT alumni Curiosity team members (from left) Bobak Ferdowsi, Al Chen, and Steve Sel to speak at a department seminar in October. Following the presentation, they joined students, faculty, and staff for a reception where they cut slices from a "Curiosity" cake.

Research

The department's total research expenditures (adjusted for dual researchers) for 2012 was $30.2 million.

AeroAstro faculty and students are engaged in hundreds of research projects under the auspices of the department's laboratories and centers. Many of the department's research projects are open to undergraduates through UROP. Research activities in other MIT laboratories and centers are open to students registered in AeroAstro.

Aerospace Computational Design Laboratory

The Aerospace Computational Design Laboratory's (ACDL) mission is the advancement and application of computational engineering for the design, optimization, and control of aerospace and other complex systems. ACDL research addresses a comprehensive range of topics, including advanced computational fluid dynamics and mechanics, uncertainty quantification, data assimilation and statistical inference, surrogate and reduced modeling, and simulation-based design techniques.

Advanced simulation methods developed by ACDL researchers facilitate the understanding and prediction of physical phenomena in aerospace systems and other applications. A long-standing interest of the laboratory has been the advancement of computational fluid dynamics for complex three-dimensional flows, enabling significant reductions in time from geometry to solution. Specific research interests include aerodynamics, aeroacoustics, flow 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 important for energy conversion and propulsion.

The ACDL's efforts in uncertainty quantification aim to endow computational predictions with quantitative measures of confidence and reliability while addressing broad underlying challenges of model validation. Complementary efforts in statistical inference and data assimilation are aimed at estimating and improving physical models and predictions by conditioning on observational data. Current research has developed effective methods for error estimation, solution adaptivity, sensitivity analysis, uncertainty propagation and the solution of stochastic differential equations, the solution of large-scale statistical inverse problems, nonlinear filtering in partial differential equations, and optimal experimental design. Applications range from aerospace vehicle design to large-scale geophysical problems and subsurface modeling.

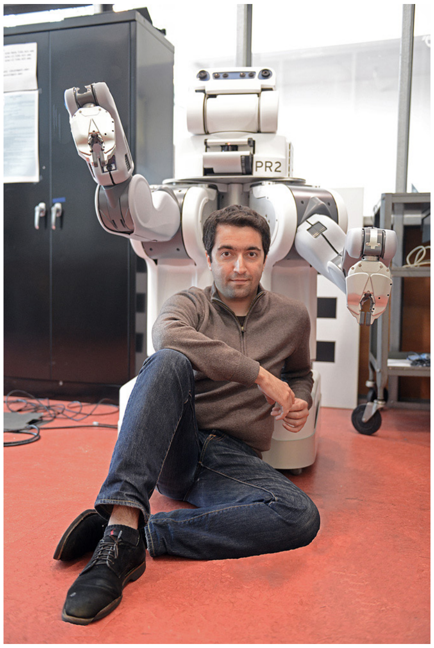
ACDL research in simulation-based design and control is aimed at developing methods to support better decision making in aerospace and other complex systems, with application to conceptual, preliminary, and detailed design. Our recent efforts have yielded effective approaches to partial differential equation (PDE)-constrained optimization, real-time simulation and optimization of systems governed by PDEs, multiscale and multi-fidelity 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 include Youssef Marzouk (director), David Darmofal, Mark Drela, Jaime Peraire, Qiqi Wang, and Karen Willcox.

Aerospace Controls Laboratory

The Aerospace Controls Laboratory (ACL) 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 the Real-time indoor Autonomous Vehicle test ENvironment (RAVEN), 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 consensus-based bundle algorith1 as a distributed task-planning algorithm that provides provably good, conflict-free, approximate solutions for heterogeneous multi-agent missions. Aside from extensions to task time-windows, coupled agent constraints, asynchronous communications, and limited network CBBA has been validated in real-time flight



Professor Sertac Karaman who joined the department in 2012, is researching means to make robots both more efficient and capable of working safely alongside humans.

test experiments. ACL has also extended its development of chance-constrained rapidly exploring random trees (CC-RRT), a robust planning algorithm to identify probabilistically feasible trajectories, to new aerospace domains. For instance, in work with professor Sertac Karaman, ACL recently developed CC-RRT*, which uses the asymptotic optimality principles of RRT* to solve robust pursuit-evasion problems. ACL is also involved in a multi-year Draper Laboratory University Research and Development Program project on precision landing of guided parafoils, with robustness to large and dynamic wind environments. Finally, ACL is participating in a multi-year, multi-university research initiative 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.

Unmanned Aerial Vehicle (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. Additionally, as part of research on long-duration UAV mission planning, ACL has constructed an autonomous recharge platform, capable of autonomous battery replacement and recharging for small UAVs. This capability allows ACL to demonstrate complex, multi-agent missions lasting for several hours.

Information-Gathering Networks: Recent ACL research has addressed maximizing information gathering in complex dynamic environments, through quantifying the value of information and the use of mobile sensing agents. The primary challenge in such planning is the computational complexity, because of both the large size of the information space and the cost of propagating sensing data into the future. ACL researchers created adaptive efficient distributed sensing in which each sensor propagates only high-value information, reducing the network load and improving scalability. 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.

Task Identification and Decision-Making: Markov Decision Processes are a natural framework for formulating many decision problems of interest. ACL has identified approximate solution techniques that 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 the incremental Feature Dependency Discovery (iFDD) algorithm, which expands the representation in areas where the sampled Bellman errors persist. Recently, this algorithm has been extended to the offline setting where it has been shown to be effective on previously collected datasets. ACL has also developed a Bayesian Nonparametric Inverse Reinforcement Learning algorithm for identifying tasks from traces of user behavior. This technique allows a user to "teach" a task to a learning agent through natural demonstrations. 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.

Aerospace Robotics and Embedded Systems group

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 systems of vehicles and mobile robots. 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 the following:

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 unmanned ground vehicles (UGVs), are increasingly being used to address complex missions for many applications, ranging from national security to environmental monitoring. An additional emphasis in this work is scalability: the objective is not only to design 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, e.g., environmental disruptions, is a well-known effect of increasing access to transportation. As infrastructure development becomes saturated, 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.

Emilio Frazzoli directs the Aerospace Robotics and Embedded Systems group.

The Autonomous Systems Laboratory

The Autonomous Systems Laboratory (ALS) is a virtual lab led by Professors Brian Williams and Nicholas Roy. Williams' group, the Model-based Embedded and Robotics (MERS) group, and Roy's Robust Robotics Group are part of the Computer Science and Artificial Intelligence Laboratory. ALS 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 acceptable levels of risk. Autonomous underwater vehicles enable scientists to explore previously uncharted portions of the ocean by performing science missions of up to 20 hours in length without the need for human intervention. Performing these extended missions can be a risky endeavor. 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.

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 such as the MIT spinoff Terrafugia offer vehicles that can both fly between local airports and 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, called PT, in which a passenger interacts with the vehicle in the same manner that he or she interacts today with a taxi driver.

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.

ASL faculty are Brian Williams and Nicholas Roy.

Communications and Networking Research Group

The Communications and Networking Research Group's (CNRG) primary goal is to design 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 on 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 (LANs).

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. Although multi-hop wireless networks can be deployed, current protocols typically result in extremely poor performance over even moderate-sized networks. Wireless mesh networks have emerged as a solution for providing last-mile internet access. However, hindering these networks' success is our relative lack of understanding of how to control wireless networks effectively, especially in the context of advanced physical layer models, realistic models for channel interference, distributed operations, and interface with the wired infrastructure (i.e., the internet). CNRG has been 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 recent pioneering research by the group. In particular, the group has been 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.

Gas Turbine Laboratory

The MIT Gas Turbine Laboratory (GTL) has had a worldwide reputation for research and teaching at the forefront of gas turbine technology for more than 60 years. The 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 and on 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, and novel aircraft and propulsion system concepts for reduced environmental impact.

Examples of current research projects include:

- A unified approach for vaned diffuser design in advanced centrifugal compressors
- A methodology for centrifugal compressor stability prediction
- Improved performance return channel design for multistage centrifugal compressors
- Investigation of real gas effects in supercritical CO2 compression systems
- Modeling instabilities in high-pressure pumping systems
- Aeromechanic response in a high-performance centrifugal compressor stage
- Ported shroud operation in turbochargers
- Manifestation of forced response in a high-performance centrifugal compressor stage for aerospace applications
- Return channel design optimization for multistage centrifugal compressors
- A two-engine integrated propulsion system
- Inlet swirl distortion effects on the generation and propagation of fan rotor shock noise
- Propulsion system integration and noise assessment of a hybrid wing-body aircraft
- Fan-inlet integration for low-fan-pressure-ratio propulsors
- Aerodynamics and heat transfer in gas turbine tip shroud cavity flows
- Secondary air interactions with main flow in axial turbines
- Compressor aerodynamics in large industrial gas turbines for power generation
- Turbine tip clearance loss mechanisms
- Flow and heat transfer in modern turbine rim seal cavities
- Modeling cavitation instabilities in rocket engine turbopumps

GTL faculty and research staff include Fredric Ehrich, Alan Epstein (emeritus), Edward Greitzer, Arthur Huang, Claudio Lettieri, Zoltan Spakovszky (director), Choon Tan, and Alejandra Uranga.

Humans and Automation Laboratory

Research in the Humans and Automation Laboratory (HAL) 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 design of 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 laboratory hosts a state-of-the-art multi-workstation collaborative teaming operations center, as well as a mobile command and control experimental test bed mounted in a Dodge Sprint van awarded through the Office of Naval Research. Current research sponsors include the Office of Naval Research, the US 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.

International Center for Air Transportation

The International Center for Air Transportation (ICAT) undertakes research and educational programs that discover and disseminate the knowledge and tools underlying a global air transportation industry that is 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 are 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 predecessor, 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.

Laboratory for Aviation and the Environment

The Laboratory for Aviation and the Environment (LAE) was founded in 1992, under the name of the Aero-Environmental Research Laboratory, by Ian A. Waitz, now dean of the MIT School of Engineering.

One of the defining challenges of the aviation industry is to address its environmental impacts—noise, effects on air quality, and role in climate change. The goal of LAE is to align the trajectory of aerospace technology and policy development with the need to mitigate these impacts. It does so by increasing the understanding of the environmental effects of aviation, by developing and assessing fuel-based operational and technological mitigation approaches, and by disseminating knowledge and tools. The laboratory also contributes to cognate areas of inquiry in aerospace, energy, and the environment. LAE researchers analyze environmental impacts and developing research tools that provide rigorous guidance to policymakers who must decide among alternatives when addressing aviation's environmental impacts. The MIT researchers collaborate with international teams in developing aircraft-level and aviation-system-level tools to assess the costs and benefits of different policies and mitigation options.

A current focus at LAE is on studying the environmental sustainability of alternative aviation fuels derived from biomass or natural gas and coal. This research includes both drop-in fuel options, which can be used with existing aircraft engines and fuel infrastructure, as well as non-drop-in options, such as liquefied natural gas, that would require modifications to aircrafts and infrastructure. Environmental metrics considered include lifecycle greenhouse gas emissions, land requirements, and water consumption. Researchers at LAE are also estimating trade-offs among different metrics and uses to better understand the full consequences of introducing a certain alternative fuel into the aviation system.

LAE has released a global emissions dataset for civil aviation emissions that represents the most current estimate of emissions publicly available. It is widely used by researchers in areas including atmospheric modeling and aviation and the environment. Other recent work investigates the public health and climate impacts of ultra-low-sulfur jet fuel and the effects of increasing airport capacity in the UK on air quality. LAE reports and publications can be accessed at http://lae.mit.edu.

The laboratory is also operational headquarters of PARTNER, a Federal Aviation Administration (FAA) Center of Excellence sponsored by the FAA, NASA, Transport Canada, the US Department of Defense, and the Environmental Protection Agency. 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. PARTNER's leadership is based at LAE, with Ian Waitz as director and Steven Barrett as associate director.

LAE faculty include Steven Barrett (director), Hamsa Balakrishnan, John Hansman, Ian Waitz, and Karen Willcox. Robert Malina is the lab's associate director.

Laboratory for Information and Decision Systems

The Laboratory for Information and Decision Systems (LIDS) at MIT 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.

Since 1939, LIDS has been at the forefront of major methodological developments that have been 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 continue to make breakthroughs that cut across traditional boundaries.

Members of the LIDS community share a common approach to solving problems and recognize the fundamental roles 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 laboratory and with the larger MIT community. Currently 17 faculty are affiliated with the laboratory, including Emilio Frazzoli, Jonathan How, Eytan Modiano, and Moe Win.

Man Vehicle Laboratory

The Man Vehicle Laboratory (MVL) 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, on the Mir space station, and on many parabolic flights, and has developed experiments for the ISS.

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. A new undertaking with Russian colleagues, under the umbrella of the MIT Skoltech Initiative, emphasizes innovative solutions to the protection and performance enhancement of astronauts during space exploration. MVL projects include the use of a short-radius centrifuge as a countermeasure, the development of a *g*-loading suit to maintain muscle and bone strength, and the logistics of resupply and mission support.

During an April 2013 visit to the Man Vehicle Lab, AeroAstro alumn Buzz Aldrin (ScD '63) poses with faculty, students, and a mannequin that's wearing one of the lab's designs for a next-generation space suit.

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 Department of Transportation's FAA and Federal Railroad Administration, the Center for Integration of Medicine and Innovative Technology, the Deshpande Center, and the MIT Portugal Program. The laboratory also collaborates with the Volpe National Transportation Research Center and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

MVL faculty include Charles M. Oman (director), Jeffrey Hoffman, Dava Newman, Laurence R. Young, and Julie Shah.

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 the understanding of materials and structures, 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 (microelectromechanical systems, or MEMS) topics. A significant effort over the past decade has been to use nanoscale materials to improve the performance of advanced aerospace materials and their structures through the industry-supported Nano-Engineered Composite Aerospace Structures (NECST) Consortium.

The necstlab group has interests that run from fundamental materials synthesis questions through to structural applications of both hybrid and traditional materials. This includes longstanding projects in MEMS and now biofunctionalized nanoelectromechanical systems (bioNEMS)/MEMS. Although not all-encompassing, much of the group's work supports the efforts of the NECST Consortium, an aerospace industry-supported research initiative that seeks to develop the understanding needed to create enhanced-performance advanced composites using nanotechnology.

Necstlab maintains collaborations around the MIT campus, particularly with faculty in the Departments of Mechanical Engineering, Materials Science and Engineering, and Chemical Engineering, and with MIT laboratories 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 necstlab are formal and informal collaborations with leading research groups from around the world.

Research projects include:

- BioNEMS materials design and implementation in microfluidics,
- Buckling mechanics,
- Carbon nanostructure synthesis from nontraditional 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,
- Silicon MEMS devices, including piezoelectric energy harvesters, microfabricated solid oxide fuel cells, stress characterization, and 3D MEMS, and
- Vertically aligned carbon nanotubes (VACNT) characterization and physical properties

The necstlab faculty include Brian L. Wardle (director) and John Dugundji (emeritus).

The Partnership for AiR Transportation Noise and Emissions Reduction

The Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) 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 potential mitigation options for environmental impacts, 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 community groups.

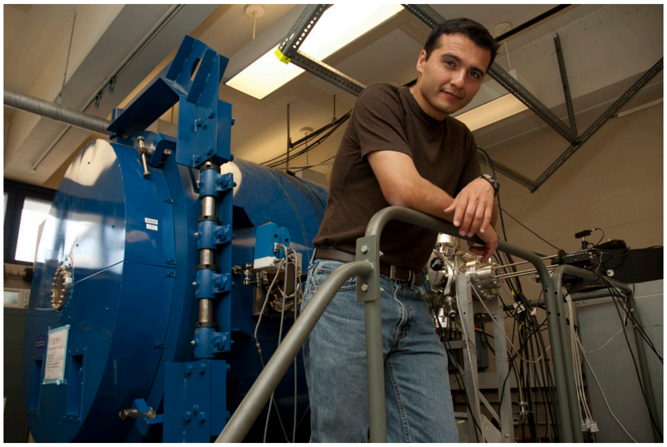
MIT's most prominent research role within PARTNER is in analyzing environmental impacts and developing research tools that provide rigorous guidance to policymakers who must decide among alternatives to address aviation's environmental impact. The MIT researchers collaborate with an international team 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 the microphysics and chemistry of aircraft particulate matter, and economic analysis of policies. PARTNER collaborators' most recent reports include Environmental Cost-Benefit Analysis of Ultra Low Sulfur Jet Fuel and CO_2 Emission Metrics for Commercial Aircraft Certification: A National Airspace System Perspective. MIT PARTNER researchers have also 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, and Karen Willcox.

Space Propulsion Laboratory

The Space Propulsion Laboratory (SPL) studies and develops systems for increasing performance and reducing costs of space propulsion and related technologies. A major area of interest to the laboratory is electric propulsion, in which electrical, rather than chemical, energy propels spacecraft. The benefits are numerous, hence electric propulsion systems are increasingly applied to communication satellites and scientific space missions. These efficient engines allow exploration in more detail of the structure of the universe, increase the lifetime of commercial payloads, and look for signs of life in far-away places. Areas of research include 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 also 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 electrospray 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, such as deformable mirrors and apertures. SPL facilities include a supercomputer cluster where plasma and molecular dynamics codes are routinely executed and there is a state-of-the-art laboratory including three vacuum chambers, clean room environment benches, and electron microscope and electronic diagnostic tools to support ongoing research efforts.



In May 2013 Professor Paulo Lozano was named director of AeroAstro's Space Propulsion Laboratory. Lozano has been working at the forefront of space propulsion technology, most notably in the area of electric propulsion.

Manuel Martínez-Sánchez directed the Space Propulsion Laboratory through April 2013; Paulo Lozano is currently the director.

Space Systems Laboratory

Space Systems Laboratory (SSL) research contributes to the exploration and development of space. The 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 operated aboard the ISS, and leadership of AeroAstro's 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, MEMS, modular space systems design, microsatellite design, real-time embedded systems, and software development.

In October 2012, the Synchronized Position Hold Engage Re-orient Experimental Satellites (SPHERES) facility on the ISS was expanded to include vision-based navigation through the Visual Estimation for Relative Tracking and Inspection of Generic Objects (VERTIGO) program, which has already begun testing. VERTIGO will be used to develop vision-based navigation and mapping algorithms through a stereo camera system and an upgraded processor. In the summer of 2013, the University of Maryland Space Power and Propulsion Laboratory, Aurora Flight Sciences, and SSL will again upgrade the SPHERES facility to include the Resonant Inductive Near-Field Generation System (RINGS), which will be used to test electromagnetic formation flight and wireless power transfer through a pair of tuned resonant coils that generate a time-varying magnetic field. Also in 2013, in partnership with the Naval Research Laboratory, SSL will design robotic arms that will be incorporated into the SPHERES facility. SSL will also work, in partnership with JPL and Aurora Flight Sciences, on the Defense Advanced Research Projects Agency's Phoenix program, which is developing the SPHERES facility to be used as a testbed for servicing and assembly missions.

Professor Sara Seager of the Department of Earth, Atmospheric, and Planetary Sciences (right) joins AeroAstro Professor Kerri Cahoy in Cahoy's Wavefront Control Laboratory behind an optical table simulation of a space telescope that will use a "coronagraph" to take direct images of Earth-like exoplanets around other stars. The coronagraph blocks the starlight while allowing researchers to see exoplanets orbiting the star.

The Wavefront Control Laboratory (WCL) develops nanosatellites, instruments, and algorithms that allow exploration of both Earth and other worlds from space. WCL demonstrates wavefront control using MEMS deformable mirrors, Shack-Hartmann wavefront sensors, and liquid crystal spatial light modulators. 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 techniques such as radio occultation and microwave radiometry, and is building a 3U dual-spinning CubeSat hosting a 1U passive microwave radiometer for MIT Lincoln Laboratory, called the Microsized Microwave Atmospheric Satellite (MicroMAS). In addition, WCL collaborates with commercial satellite companies to investigate the connection between on-orbit component anomalies and space weather for geostationary communications spacecraft (http://web.mit.edu/cahoylab).

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 (MicroMAS, in collaboration with MIT Lincoln Laboratory); a cluster flight of three 3U CubeSats equipped with electrospray microthrusters called MotherCube (in collaboration with MIT AeroAstro's SPL 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 Draper Laboratory) called ExoplanetSat. Also under development is TERSat (trapped energetic radiation satellite) for precipitation of energetic particles from the radiation belts, previously under the Air Force's University Nano-satellite Program (in collaboration with SPL).

SSL is also designing the regolith X-ray imaging spectrometer (REXIS), an instrument that will be flown on NASA's OSIRIS-REx asteroid sample return mission (launch scheduled for 2016). REXIS will use charged-coupled detectors as an x-ray spectrometer to characterize the surface of asteroid 1999 RQ36. The project, which has included the work of more than 50 undergraduate and graduate students, is successfully through its preliminary design review and working toward its critical design review in 2014.

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 the ISS based on radio frequency identification technology. Together with JPL, 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 Martínez-Sánchez, Paulo Lozano, Sara Seager, Alvar Saenz-Otero, Rebecca Masterson, Steve Ulrich, and Alessandra Babuscia.

System Engineering Research Laboratory

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 new technology and the increasing complexity of the systems we are building. Software is changing the causes of accidents and a human operating such a system has 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 systems in which our systems are designed and operated.

The System Engineering Research Laboratory's goal is to create tools and processes that will 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. The Laboratory for Systems Safety Research 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) and in spacecraft, medical devices and healthcare, automobiles, railroads, nuclear power, defense systems, energy, and large manufacturing and processing 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

Nancy Leveson directs the System Engineering Research Laboratory.

Technology Laboratory for Advanced Materials and Structures

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

- 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 to address the role of length scale in the failure of composite structures
- Numerical and analytical solid modeling to inform, and be informed by, experiments
- 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 composite, 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 and for testing at low and high temperatures 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, along with the capability 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 research affiliate Antonio Miravete.

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; such networks 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 laboratory.

The laboratory 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 gigahertz. 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 under way to analyze the vast amounts of data collected during an extensive measurement campaign that was completed in early 2009.

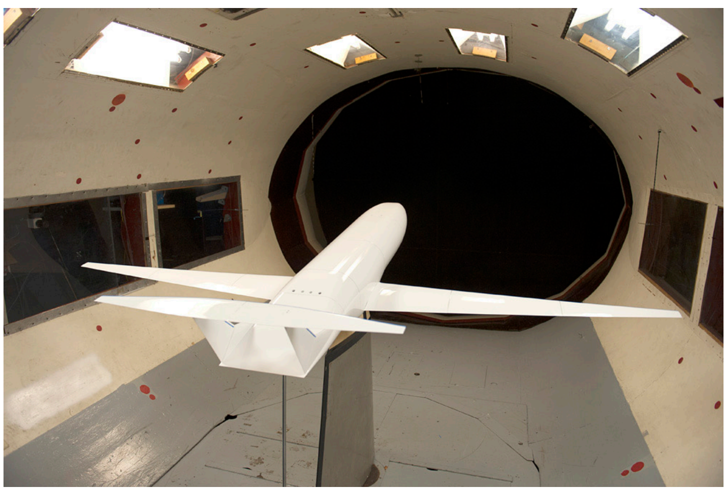
The group's students are also investigating physical-layer security in large-scale wireless networks. Such security schemes will play increasingly important roles in new paradigms for guidance, navigation, and control of UAV networks. The framework they have developed introduces the notion of a secure communications graph that 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 proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and sectorized transmission. They also 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 UROP and the MIT Summer Research Program. Professor Win maintains dynamic collaborations and partnerships with academia and industry, including the University of Bologna and the University of Ferrara in Italy, Lund University in Sweden, the University of Oulu in Finland, the National University of Singapore, Nanyang Technological University in Singapore, Draper Laboratory, NASA's Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Moe Win directs the Wireless Communication and Network Sciences Group.

Wright Brothers Wind Tunnel

Since its opening in September 1938, the Wright Brothers Wind Tunnel (WBWT) has played a major role in the development of aerospace and 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 FAA. There have also been tests of Olympic ski gear, of space suits for tare evaluations related to underwater simulations of weightless space activity, and of racing bicycles, subway station entrances, and Olympic rowing shells for oarlock system drag comparisons.



A 1:10 model of the D-8 commercial aircraft concept is prepared for testing in AeroAstro's Wright Brothers Wind Tunnel. Designed by an MIT-led team, the 737-size plane could burn 70 percent less fuel than current aircraft while reducing noise and nitrous oxide emissions.

In its more than 70 years of operation, WBWT work has been recorded in hundreds of theses and more than 1,000 technical reports.

WBWT faculty and staff include Mark Drela and Richard Perdichizzi.

The Learning Laboratory

The AeroAstro Learning Laboratory, located in Building 33, promotes student learning by providing an environment for hands-on activities that span the department's CDIO educational paradigm.

The Learning Laboratory comprises four main areas:

- *Robert C. Seamans Jr. Laboratory.* The Seamans Laboratory occupies the first floor. It includes:
    - *The Concept Forum*—a multipurpose room for meetings, presentations, lectures, videoconferences and collaboration, distance learning, and informal social functions. In the Concept Forum, students work together to develop multidisciplinary concepts and to learn about program reviews and management.
    - *Al Shaw Student Lounge*—a large, open space for social interaction.
- *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 their last year at MIT. The Gelb facilities are designed to foster teamwork with a variety of resources to meet the needs of curricular and extracurricular 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 to (and networked to) the main Digital Design Studio are two smaller design rooms: the Department of Aeronautics and Astronautics 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 located for convenient assistance in an office adjacent to the Design Center.

Some of the projects undertaken by students in the Learning Laboratory 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.

Degree Programs

The bachelor of science (SB) degree is a four-year program designed to prepare each graduate for an entry-level position in the aerospace field and for further education at the master's level. The curriculum is flexible enough to give students options in their pursuit of careers in aerospace, ranging from fundamental research to responsible engineering leadership of large enterprises. The required undergraduate curriculum provides a core around which students can build in pursuit of becoming practicing engineers on receipt of the undergraduate degree, continuing on to graduate studies in any of the specialties, or following fields outside engineering.

In academic year 2013, the 16-1 and 16-2 degrees were combined into a single degree program (16 – Aerospace Engineering). The combined program retains the previous deep emphasis on the fundamentals and provides strong integration within the overarching CDIO context.

There is an informal option in aerospace information technology for those students who select at least three professional area subjects from a designated list. There is no notation of the option on the diploma or transcript.

The Department of Aeronautics and Astronautics also offers a relatively new, more flexible program, Course 16-ENG, which emphasizes aerospace-related engineering. Given that the practice of aerospace engineering has become increasingly multidisciplinary, a more flexible degree provides the opportunity to address educational needs for the expanding envelope of aerospace and related systems. More, the flexible degree program builds on the department's strength in collaborative, multidisciplinary problem solving.

The skills and attributes emphasized in all the department's programs go beyond the formal classroom curriculum and include modeling, design, the ability to self-educate, computer literacy, communication and teamwork skills, ethical context, and appreciation of the interfaces and connections among various disciplines. Opportunities for formal and practical training in these areas are integrated into departmental subjects through examples set by the faculty, by the disciplinary content, and by the opportunity for substantive engagement. The curriculum also includes opportunities for students to participate in study-abroad programs.

AeroAstro offers doctoral degrees (PhD and ScD) that emphasize in-depth study with a significant research project in a focused area. Entrance to the doctoral program requires students to pass a graduate-level examination in a field of aerospace engineering as well as to demonstrate an ability to conduct research in the field. The doctoral degree is awarded after completion of an individual course of study, submission and defense of a thesis proposal, and submission and defense of a thesis embodying an original research contribution.

In addition, the department participates in a variety of interdisciplinary graduate programs.

Graduate Enrollment*

	07-08	08-09	09-10	10-11	11-12	12-13
Total Graduate Student Body	226	236	226	226	229	246
SM**	146	148	130	111	121	125
PhD†	80	88	96	115	108	121
Minority						
SM	8	8	9	7	9	12
PhD	5	6	4	6	5	6
Female						
SM	29	32	30	22	21	23
PhD	19	23	17	20	16	22

*Numbers based on the registrar's fall fifth week enrollment reports.

**Includes students pursuing only the master's degree and students who have not yet passed the doctoral qualifying exam.

†Students who have passed the doctoral qualifying exam.

Undergraduate Enrollment

	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12	12-13
Sophomores	72	64	65	65	65	74	57	51	45	66
Juniors	59	59	52	60	66	55	65	47	46	43
Seniors	61	65	76	56	66	62	58	68	47	45
Totals	**192**	**188**	**196**	**181**	**189**	**191**	**180**	**166**	**138**	**154**
% Women	34%	30%	26%	31%	30%	30%	34%	29%	31%	37%
% URM	30%	27%	25%	19%	14%	32%	40%	28%	38%	30%

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