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 that are 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 footprint that belies its size. AeroAstro saw an increase this year in total undergraduate enrollment, to 168 from 154. And with just under 250 students, the graduate program remains highly competitive.

There were 36 faculty members in the department at the end of academic year 2014 (32.5 full-time equivalents after accounting for dual appointments). Two highly esteemed and long-term colleagues, Manuel Martinez-Sanchez and Larry Young, retired in January. AeroAstro welcomed Leia Stirling to its faculty. Leia started in July 2013 as an assistant professor affiliated with the Man Vehicle Laboratory, with research interests in computational dynamics, system automation, human factors, experimental biomechanics, and human–machine interaction for aerospace and medical applications. Earlier this year, David Miller was named NASA's chief technologist, making a two-year leave of absence from the Institute necessary.

A department centered on a dynamic industry, AeroAstro completed a new strategic plan, with the objective of developing a guiding strategy—a strategic initiative—for the upcoming decade. As part of this exercise, the department identified a set of core competencies that are critical to sustaining its intellectual breadth and depth, maintaining its competitive advantage, and supporting a broad education program. The core competencies are vehicle design, information sciences, computation, human–system collaboration, atmosphere and space sciences, and complex systems. AeroAstro has made the commitment to evolve and strengthen these competencies, internally and through collaboration across MIT and external partners. Integration across competencies enables AeroAstro to pursue new strategic opportunities. The department has identified four strategic avenues: air transportation, autonomous systems, small satellites, and aerospace engineering education. These represent emerging opportunities in aerospace with significant potential effects and they are aligned with the department's competencies. AeroAstro will approach these challenges by building on the individual strengths of its faculty and by collaborating with colleagues inside and outside MIT.

Vision, Mission and Strategy

The department aspires to enable novel aerospace and related systems through education, research, and leadership, and to use these systems to inspire future generations of engineers, leaders, and innovators who are critical thinkers possessing both a deep technical understanding and a systems perspective.

The mission of the MIT's Department of Aeronautics and Astronautics is:

- To educate tomorrow's leaders through innovative educational programs and pedagogies that have as their context the conception, design, implementation, and operation of aerospace systems and processes;
- To conduct research that generates inventions, technologies, and solutions to aerospace and related engineering problems, in collaboration with colleagues at MIT, other universities, industry, and government in the United States and abroad; and
- To provide leadership to the Institute and to the national and international aerospace and engineering communities.

AeroAstro's strategy has the following elements:

1. To build a stronger faculty by hiring for excellence, mentoring, and promoting collaboration;
2. To enhance excellence in graduate and undergraduate education by reinvigorating the department's commitment to the development, assessment, and continuous improvement of its pedagogy and of its students' learning; and
3. To improve its physical space by enhancing maintenance procedures and investing in space renovations.

Professor Mark Drela and research scientist Uranga Alejandra prepare a model of the MIT-designed D-8 aircraft for testing in NASA's Langley, Virginia wind tunnel. A 737-size commercial aircraft design, the D-8 has the potential of achieving a 70 percent reduction in fuel use compared to current aircraft

Promoting Faculty Excellence

Department faculty members meet weekly, providing a forum for research presentations, departmental updates, and general discussion. The department welcomes individuals from other units across campus to make presentations at these meetings. Outside presentations during AY2014 included a talk by Charles Stark Draper Laboratory researchers, "Science-Engineering Connections," and presentations on other topics, such as "Discussion on New Entity for Information and Decision Sciences, Sociotechnical Systems, and Statistics," "Translating Ideas from the Academic Laboratory to Commercial Impact," "SuperUROP and the MEng program in Electrical Engineering and Computer Science," and "MIT Nano-Construction Impact." These weekly meetings are a mainstay of department life and allow faculty to stay connected to one another and to the Institute.

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

Promotions

Professor Steven Barrett was promoted to the rank of associate professor without tenure, effective July 1, 2014.

Recognition

- Professor Ed Greitzer was named an American Institute of Aeronautics and Astronautics (AIAA) Honorary Fellow.
- Professor Paolo Lozano was named an AIAA Associate Fellow.
- Professor Nick Roy was named an AIAA Associate Fellow.
- Professor Wes Harris received MIT's 2014 Martin Luther King, Jr., Lifetime Achievement Award.
- Professor Zolti Spakovszky was elected as a fellow of the American Society of Mechanical Engineers.
- Professor Raul Radovitzky received an MIT award recognizing his work as a freshman faculty advisor.
- Professor Qiqi Wang is one of 42 scientists and engineers selected this year by the Young Investigator Program of the US Air Force Office of Science.
- The AIAA Advising Award was given to Hamsa Balakrishnan.
- The AIAA Undergraduate Teaching Award was given to Ed Greitzer.
- Professor David Miller was named as NASA's chief technologist.

Promoting Excellence in Graduate Education

The department's graduate program was again ranked #1 in the country by *U.S. News and World Report*. AeroAstro received 521 applications for admission to its graduate programs, admitting 91 applicants (admission rate of 17%). Of the 91 admitted, 71 students enrolled, for a yield of 78%.

Continuing the tradition of formal end-of-semester progress reviews, department faculty provide written evaluations each semester, and hold regular review meetings with all graduate students in an effort to enhance professional development, feedback, and mentoring. Professors Peraire and Modiano 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

- The first prize in GA^3's 2014 PhD Research Competition went to Allie Anderson; runners-up were Krish Kotru and Chelsea He.
- The AIAA Teaching Assistantship Award was given to James Wiken. The AeroAstro Graduate Teaching Assistantship Award, given to a graduate student who has demonstrated conspicuous dedication and skill in helping fulfill an undergraduate or graduate subject's educational objectives, went to Aaron W. Johnson.
- Sreeja Nag was presented with the Luigi G. Napolitano Award at this year's International Astronautical Congress for a paper she presented on the bidirectional reflectance distribution function. The award is presented "to a young scientist, below 30 years of age, who has contributed significantly to the advancement of the aerospace science and has given a paper at the International Astronautical Congress on the contribution."
- Philip Wolfe has been named the US Department of Transportation, Federal Aviation Administration Centers of Excellence Student of the Year.
- Professor Julie Shah and PhD student Matthew Gombolay's paper, "A Uniprocessor Scheduling Policy for Non-Preemptive Task Sets with Precedence and Temporal Constraints," from the 2012 AIAA Infotech@Aerospace Conference, was chosen by the AIAA Intelligent Systems Technical Committee as the AIAA Best Intelligent Systems Paper from 2012.
- For the second year in a row, a team of authors associated with the Aerospace Controls Laboratory has been cited by the AIAA Guidance, Navigation, and Control Technical Committee for Best Paper at its Guidance, Navigation, and Control Conference. The authors were PhD candidate Kemal Ure, Tuna Toksoz (SM '12), Josh Redding (PhD '12), postdoctoral associate Girish Chowdhary, Aerospace Controls Laboratory director Jon How, and Boeing Technical Fellow John Vian.

Promoting Excellence in Undergraduate Education

The department was and is strongly committed to promoting undergraduate research, hiring a number of students through the Undergraduate Research Opportunity Program (UROP). In AY2014, AeroAstro filled 241 UROP positions, of which 18% were filled by freshmen. During summer 2014, 38 of the department's 68 UROP students (55.8%) 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. The associate department head then meets with all instructors of undergraduate subjects to review what had happened in the past term and make plans for future improvements.

Recognition

- Lindsay M. Sanneman '14, Travis L. Wagner '14, and Alexandra E. Wassenberg '14 were given the Apollo Program Prize, given to an AeroAstro student who conducts the best undergraduate research project on the topic of humans in space.
- The 2014 Design-Build-Fly Team (Jeff Chen, Casey Denham, Sara Gonzalez, Rachel Harris, Libby Jones, Allan Ko, Giula Pantalone, Tony Tao, Harry Thaman, and J. Marcel Williams) received the Leaders for Manufacturing Undergraduate Prize, given to a student team that has demonstrated excellence or innovation, or both, in addressing the interaction between manufacturing and engineering during the execution of their project.
- Jason D. Elizalde '15 and Eduardo N. Seyffert '14 received the United Technologies Corporation Prize, awarded to an AeroAstro student or students for outstanding achievement in the design, construction, execution, and reporting of an undergraduate experimental project.
- Elizabeth Y. Qian '14 and Naomi D. Schurr '14 were awarded the Admiral Luis De Florez Prize, awarded for "original thinking or ingenuity."
- William C. Thalheimer '14 received the James Means Award for Excellence in Flight Vehicle Engineering.
- Matthew T. Vernacchia '15 received the James Means Award for Excellence in Space Systems Engineering.
- James R. Clark '14 and Karly E. McLaughlin '15 received the Thomas B. Sheridan Award, which is given to an AeroAstro or Mechanical Engineering undergraduate student or students whose research or design project best exemplifies creativity or improvement in human–machine integration or cooperation.
- Elizabeth Y. Qian '14 received the Henry Webb Salisbury Award, given in memory of Henry Salisbury to a graduating senior who has achieved superior academic performance in the Course 16 Undergraduate Program.
- Elizabeth A. Jones '14 was given the AeroAstro Undergraduate Teaching Assistantship Award, which is awarded to an undergraduate student who has demonstrated conspicuous dedication and skill in helping to fulfill an undergraduate subject's educational objectives.
- James M. Byrne 14 and Melissa L. Kornspan '14 were both awarded the Rene H. Miller Prize in Systems Engineering, given to a student "who has done the best piece of work in systems engineering in the AeroAstro department."
- Janelle P. Mansfield '15 received the Yngve Raustein Award, given to a Unified Engineering student who best exemplifies the spirit of Yngve Raustein and also to recognize significant achievement in Unified Engineering.

Improving AeroAstro's Physical Space

The AeroAstro departmental space committee has been actively improving the quality of the department's facilities. The department has continued to make use of new protocols for reporting problems and maintenance issues; this has shortened the response time for repairs. AeroAstro upgraded the audiovisual equipment in Room 33-218 and installed additional LED information screens in several locations to keep department members informed of the latest news and to showcase our research. The department also installed a timeline on the second floor of Building 33 to highlight the historic contributions the department has made to AeroAstro engineering.

The department continues to struggle with its working space. Because of its age and condition, much of the office and research space in the department is considered below par, placing MIT AeroAstro at a competitive disadvantage. This is especially worrisome given the construction of new, world-class facilities at Stanford and Caltech, MIT's closest rivals for graduate students and faculty. AeroAstro is currently renovating some newly acquired space for students on the third floor of Building 37. This space will be open and flexible by design and allow the students in AeroAstro's largest laboratory, the Aerospace Computational Design Laboratory (ACDL), to benefit from a vastly improved layout with access to natural light. AeroAstro has also built two new laboratories in Building 35; these will open in September 2014. These laboratory spaces will provide additional research space for professor Paulo Lozano's Space Propulsion Laboratory (SPL), which will focus on microsatellites, and Professor Brian Wardle's necstlab, which explores new concepts in engineered materials and structures.

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."

AeroAstro is currently in the schematic design phase of the renovation of Building 31. After this renovation there will be vastly improved student space as well as a new, world-class high-bay flight area for both robotics and unmanned aerial vehicle (UAV) research.

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 with education. Renovations must be a department priority in order to put both the research and educational missions back on track. AeroAstro has been asked by the Department of Facilities to address this after the construction of MIT.nano unless there is a catastrophic failure, which would require immediate attention.

Resource Development

Over AY2014, the department focused on securing the funds to enable the renewal of Building 31. With the help of Marco Munoz in Global Initiatives and the Office of Resource Development, AeroAstro prepared and delivered two $25 million proposals to Miguel Aleman and Emilio Azcarraga to help with the Building 31 renewal and other AeroAstro priorities (both still pending). AeroAstro also delivered a $10 million proposal in support of the renovation to MIT alumnus Kent Kresa with the help of John Currier of MIT's Office of Philanthropic Partnerships; this proposal was accepted. The signed document arrived in the last week of June and has enabled the Building 31 project to move forward with the pending signing of the ITA agreement. Other donors have been engaged throughout the year to support department-based fellowships (alumnus Dan Schwinn has donated $75,000 annually) and also to support AeroAstro's Science Technology Engineering Math (STEM) program at MIT for sixth-, seventh-, and eighth-graders from Boston public schools. The STEM outreach program Zero Robotics received $100,000 from the Northrop Grumman Foundation.

This year also marks the 100th anniversary of the first aeronautics course at MIT. The department's first alumni event in celebration of the anniversary took place in Seattle in May, when development officer Mark Veligor and department head Jaime Peraire traveled to the area to meet with prospective donors and host 90 MIT alumni at the Museum of Flight at Boeing Field (officially King County International Airport). Other alumni events took place in Washington, DC, Los Angeles, CA, New York, NY, and on campus, led by Mark Veligor. Many AeroAstro professors participated, including Paulo Lozano, David Miller, Kerri Cahoy, and Oli de Weck. Department staff are now working with the alumni association and resource development office to plan AeroAstro's centennial symposium this fall and also set up future trips to Los Angeles and Washington, DC, for alumni events and prospect cultivation.

Outreach

Professor Julie Shah, along with members of the department staff and student body, hosted the department's third Freshman Pre-Orientation Program (FPOP)—Discover Aerospace—in August 2013. Attended by 29 freshmen, the four-day event was a rousing success. The students engaged in hands-on design (balsa airplanes and bottle rockets) and a rocket launch competition in Briggs Field, visited NASA's Chandra Observatory in Cambridge, and received a preview of life in the department. FPOP again proved an exciting time for the students and a wonderful opportunity for the department to connect, inspire, and recruit. Looking ahead to AY2015, AeroAstro is delighted to report that 18 of the 29 students who participated in Discover Aerospace (62%) have declared AeroAstro as their major.

In 2009, the Space Systems Laboratory (SSL) expanded the uses of the synchronized position hold engage and reorient experimental satellites (SPHERES) facility to include STEM outreach through an exciting program called Zero Robotics, which engages high-school and middle-school students in a competition aboard the International Space Station (ISS) using SPHERES (http://zerorobotics.mit.edu). A pilot program began in 2009 with two teams from Idaho. The program expanded to include approximately 100 US and 50 European teams annually from 2010–2013. In 2013, three astronauts (Barbara Morgan, Gregory Johnson, and Gregory Chamitoff) and the director (Gavin Hood) and special effects supervisor (Mattew Buttler) of *Ender's Game* joined AeroAstro and the finalists as they saw their code run on the satellites aboard the ISS in real time by video downlink.

The department held its sixth Women in Aerospace Symposium in April 2014. An annual tradition, the event provides the department a unique opportunity to foster a network among top women doctoral students in aerospace. Sheila Widnall, AeroAstro faculty member, Institute Professor, and former secretary of the Air Force, was the 2014 keynote speaker. Department guests included women from Caltech, Georgia Tech, Harvard University, Princeton University, Purdue University, Rensselaer Polytechnic Institute, Stanford University, the University of Colorado, the University of Maryland, the University of Michigan, the University of Texas, and the University of Texas at Austin.

AeroAstro held an Open House on Wednesday, April 23, 2014—a rare event, meant to mark the 100th anniversary of MIT's (and the country's) first aeronautics course. There were many activities, open laboratories, displays, and so on. Just a few of the activities were:

- Step inside the Wright Brothers Wind Tunnel,
- Build a mini-parachute and see if you can drop an egg from two stories up without it breaking,
- Take the controls of a virtual airplane,
- Operate a microsatellite just like ones aboard the ISS,
- Get very close to actual jet engines dating from World War II to today, and
- Visit the Gas Turbine Laboratory, Interactive Robotics Laboratory, and Laboratory for Aviation and the Environment.

During AeroAstro's April 23, 2014 Open House, Grad student Sam Schreiner helps a young visitor launch an air-powered rocket she made.

Departmental Awards

Quentin Alexander was the recipient of the Wings Award, which was established to recognize an individual support staff member in AeroAstro for excellence.

Anthony Zolnik, department space manager for AeroAstro, 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 Patrick Blonigan, a graduate student in AeroAstro.

A Remarkable Year

In November 2013, the department hosted a one-day symposium celebrating the 20th anniversary of STS-61, the first Hubble space telescope-servicing mission. In addition to AeroAstro's own Jeff Hoffman, Story Musgrave, Dick Covery, Ken Bowersox, and Tom Akers —five of the seven astronauts from the mission—were in attendance. It was a great event whose participants revisited the experiences of the crew and others who made this feat possible and gained appreciation for the remarkable science that has been enabled by the Hubble telescope in the past 20 years.

In the spring semester, AeroAstro started a Centennial Seminar Series that will run through academic year 2015. The inaugural centennial seminar was given by General Janet Wolfenbarger, USAF, the first female four-star general in the Air Force and one of only three female four-star generals in U.S. military history. General Wolfenbarger, a Course 16 alumna, gave an outstanding presentation and later fielded questions. Other Centennial Seminars are planned, including talks by Jean Botti, chief technical officer of Airbus Group, and Mark Lewis, director of the Science and Technology Policy Institute at the Institute for Defense Analyses.

The high point of the celebration will be a three-day centennial symposium on October 22–24. The department's guests will include luminaries of the aerospace field—names familiar to all. These include several of the original Apollo astronauts, including three of the four Course 16 alumni to have walked on the moon, and a dozen or more space shuttle and ISS astronauts, industry leaders, and policy makers.

Research

The department's total research expenditure (adjusted for dual appointments) for 2013 was $32.25 million.

AeroAstro faculty members 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 Undergraduate Research Opportunities Program (UROP). In addition, research activities in other MIT laboratories and centers are open to students registered in the Department of Aeronautics and Astronautics.

Aerospace Computational Design Laboratory

The Aerospace Computational Design Laboratory's 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 extend to chemical kinetics, transport-chemistry interactions, and other reacting flow phenomena important for energy conversion and propulsion.

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. Recent efforts yielded effective approaches to 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 are Youssef Marzouk (director), David Darmofal, Mark Drela, Jaime Peraire, Qiqi Wang, and Karen Willcox. Research staff include Steven Allmaras, Robert Haimes, and Cuong Nguyen.

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 such areas 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. There is a ground projection system that enables real-time animation of the planning environment, beliefs, uncertainties, intentions of the vehicles, predicted behaviors (e.g., trajectories), and confidence intervals of the learning algorithms. Recent research includes the following:

Robust Planning in Uncertain Environments: ACL developed a consensus-based bundle algorithm (CBBA) 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 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, ACL recently developed CC-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 multiyear, 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.

UAV Mission Technologies: ACL has recently demonstrated autonomous, closed-loop UAV flight in MIT's Wright Brothers Wind Tunnel. This novel capability allows ACL to test flight controllers for windy environments in a controlled and systematic manner. ACL has also 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 that is 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 and partially observable Markov decision processes are natural frameworks for formulating many decision making problems of interest. ACL has identified approximate solution techniques that can utilize this framework while lessening the curse of dimensionality and the curse of history typically encountered for exact solutions. 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. ACL has also enabled fast, real-time learning in combination with cooperative planning in uncertain and risky environments, while maintaining probabilistic safety guarantees for overall system behavior. Finally, by efficiently using potentially inaccurate models of physical systems, ACL has developed a method that minimizes samples needed in real-world learning domains, such as a car learning to race around a track.

Robust State Estimation: Many navigation and robotic mapping systems are subject to sensor failures and sensor noise that do not match the assumed system models. In many cases, this model mismatch can cause divergence of the state estimates and poor navigation system performance. ACL has developed several robust state estimation algorithms that address these issues by learning a model for the sensor noise while simultaneously generating the navigation solution. These algorithms apply hierarchical and nonparametric Bayesian models, along with inference techniques such as expectation-maximization and variational inference, to learn the noise models. In practice, the robust algorithms provide significantly more accurate solutions while requiring little additional computation relative to non-robust state estimation techniques. ACL has also applied this Bayesian framework to the simultaneous localization and mapping (SLAM) problem to develop algorithms for vision-based SLAM that are robust to landmark misidentifications that cause non-robust SLAM algorithms to fail catastrophically.

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.

Autonomy and Future Urban Mobility: Autonomous, self-driving cars are no longer the stuff of science fiction—they will be ready for commercial deployment soon. The group's work on self-driving vehicles is very broad, spanning the whole spectrum from technology development to the analysis of the socioeconomic impacts of such technology. Recent work includes:

- Affordable autonomy: can safe and reliable self-driving vehicles be designed and built at a cost that makes them affordable to the general public? The demonstration vehicles at the Singapore-*MIT* Alliance for Research and Technology were developed with computers and sensors that cost less than $30,000.

- Provable safety: how do we make sure that the vehicle will behave safely and will follow all the rules of the road? The group has developed algorithms that provably satisfy all "hard" rules, while minimizing violations of "soft" rules or recommendations.
- Autonomy for mobility on demand: How would self-driving vehicles affect urban mobility in the future? The group envisions fleets of shared self-driving vehicles, is developing algorithms for their sizing and operations, and analyzes their effects using real data from several cities worldwide.

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. Areas of focus include optimality and robustness, as well as provable safety and correctness with respect to temporal-logic specifications (e.g., rules of the road). 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 unmanned aerial vehicles and unmanned ground vehicles, 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; the 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, are well-known effects 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.

Emilio Frazzoli directs the Aerospace Robotics and Embedded Systems group.

The Autonomous Systems Laboratory

The Autonomous Systems Laboratory (ASL) is a virtual laboratory led by professors Brian Williams and Nicholas Roy. Williams's Model-based Embedded and Robotics (MERS) Group and Roy's Robust Robotics Group are part of the Computer Science and Artificial Intelligence Laboratory. 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 on the basis of engineering and world models.

Below are descriptions of several recent demonstrations.

- One demonstration concerned operating autonomous vehicles to maximize utility in an uncertain 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 long 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 for the autonomous vehicle is to help the passenger rethink his or her goal when the original goal can no longer be met. Companies such as the MIT spinoff Terrafugia offer vehicles that can fly between local airports and can travel on local roads. To operate these vehicles, one must be 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 in which one would interact today with a taxi driver.
- A third demonstration involves human–robot interaction between an astronaut and the Athlete Lunar Rover. The MERS group 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 incorporating 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-limbed, wheeled lunar rover that performs heavy lifting and manipulation tasks by using its legs as arms.

Brian Williams and Nicholas Roy are the ASL faculty.

Communications and Networking Research Group

The Communications and Networking Research Group's 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. 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 the 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 (e.g., 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 Gas Turbine Laboratory'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
- 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 using adjoint method for multistage centrifugal compressors
- Multiparameter control for centrifugal compressor performance optimization
- Performance improvement of a turbocharger twin-scroll type turbine stage
- A two-engine integrated propulsion system
- Propulsor design for exploitation of boundary layer ingestion
- An acoustic shielding method for assessment of turbomachinery noise in advanced aircraft configurations
- 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
- Diagnostics and prognostics for gas turbine engine system stability characterization
- Investigation of the origins of short-wavelength instability inception in axial compressors
- Assessment of thermal effects on compressor transients

Faculty and research staff include Daniel Cuppoletti, David Darmofal, Fredric Ehrich, Alan Epstein (emeritus), Edward Greitzer, Arthur Huang, Claudio Lettieri, Zoltan Spakovszky (director), Choon Tan, Neil Titchener, 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. Applying human-centered design principles to human supervisory control problems, and identifying ways in which humans and computers can leverage the other's strengths 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. Laboratory 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 operations center and 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 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 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.

Laboratory for Aviation and the Environment

The Laboratory for Aviation and the Environment (LAE) was founded in 1992 as 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 aviation's environmental impact—noise, effects on air quality, and contribution to climate change. LAE's goal is to align the trajectory of aerospace technology and policy development with the need to mitigate these effects. 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 are analyzing 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 LAE focus is on studying the environmental sustainability of alternative aviation fuels from biomass or natural gas. This research includes both drop-in fuel options, which can be used with existing aircraft engines and fuel infrastructure, and non-drop-in fuel options such as liquefied natural gas, which would require modifications to aircraft and infrastructure. The 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 developed and publicly released a code that allows the modeling and evaluation of emissions and their effects throughout the troposphere and stratosphere in a unified fashion. LAE has also recently released a new global emissions dataset for civil aviation emissions that is the most current estimate of emissions publicly available. It is widely used by researchers in areas such as atmospheric modeling and aviation and the environment.

Other recent work quantifies air pollution and associated health effects attributable to the different economic sectors in the United States, and the environmental and economic impacts of higher-octane gasoline in road transportation.

LAE faculty includes Steven Barrett (director), Robert Malina (associate director), Hamsa Balakrishnan, John Hansman, Ian Waitz, and Karen Willcox. Also associated with LAE are Ray Speth, research scientist, and Brian Yutko, postdoctoral associate.

Laboratory for Information and Decision Systems

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

Since 1939, LIDS has been at the forefront of major 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 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 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 laboratory and with the larger MIT community.

AeroAstro faculty affiliated with the laboratory are Emilio Frazzoli, Jonathan How, Eytan Modiano, and Moe Win.

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 conceive-design-implement-operate 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, where students work together to develop multidisciplinary concepts and learn about program reviews and management; and the 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 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, such as planetary rovers, autonomous vehicles, and reentry 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 studio are two smaller design rooms, the AA (AeroAstro) 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 located for convenient assistance in an office adjacent to the Design Studio.

Man Vehicle Laboratory

The Man Vehicle Laboratory (MVL) improves the understanding of human physiological and cognitive capabilities as applied to human-vehicle and human-robotic system safety and efficacy, as well as decision making augmented by technological aids. MVL develops countermeasures and display designs to aid pilots, astronauts, clinicians, patients, soldiers, 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 the space shuttle, the Mir space station, and on many parabolic flights, and has developed experiments for the ISS.

Space applications include 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. Ongoing work includes the development of countermeasures using a short-radius centrifuge and development of a *g*-loading suit to maintain muscle and bone strength. New major projects include a collaborative study of adaptation in roll tilt perception and manual control to altered gravity environments, using a centrifuge at the Massachusetts Eye and Ear Infirmary, and a study with the University of California, Davis, on customized and just-in-time space telerobotics refresher training. Non-aerospace projects include locomotive cab automation and displays, advanced helmet designs for brain protection in sports and against explosive blasts, the development of wearable sensor systems and data visualizations for augmenting clinical decision making, and data fusion for improving situation awareness for dismounted soldiers. A new initiative with Russian colleagues emphasizes innovative solutions to the protection and performance enhancement of astronauts during space exploration.

Research sponsors include NASA, the National Space Biomedical Research Institute, the Office of Naval Research, the Department of Transportation's Federal Aviation Administration and Federal Railroad Administration, the C. S. Draper Laboratory, the Center for Integration of Medicine and Innovative Technology, the Deshpande Center, the MIT Skoltech Program, and the MIT Portugal Program. 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, Jeffrey Hoffman, Dava Newman, Laurence Young, Julie Shah, and Leia Stirling. They teach subjects in human factors engineering, space systems engineering, real-time systems and software, space policy, flight simulation, space physiology, aerospace biomedical engineering, the physiology of human spatial orientation, statistical methods in experimental design, and leadership. The MVL also serves as the office of the director for the National Space Biomedical Research Institute–sponsored Harvard-MIT Health Sciences and Technology Graduate Program in Bioastronautics (Laurence Young), the Massachusetts Space Grant Consortium (Jeffrey Hoffman), and the MIT Portugal Program's Bioengineering Systems focus area (Dava Newman).

necstlab

The necstlab (pronounced "next lab") research group explores new concepts in engineered materials and structures, with a focus on nanostructured materials. The group's mission is to lead the advancement and application of new knowledge in understanding 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 microfabricated (microelectromechanical systems, or 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 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. Much of the group's work supports the efforts of the NECST Consortium to develop the underlying understanding needed to create enhanced-performance advanced composites using nanotechnology. In addition to the NECST Consortium members, necstlab research is supported directly or through collaboration by industry, the Air Force Office of Scientific Research, the Army Research Office, NASA, the National Institute of Standards and Technology, the National Science Foundation, the Office of Naval Research, and others.

The necstlab group maintains collaborations around the MIT campus, particularly with faculty in the Mechanical Engineering, Materials Science and Engineering, and Chemical Engineering departments, and with MIT laboratories and centers, including the Institute for Soldier Nanotechnologies, the Materials Processing Center, the Center for Materials Science and Engineering, and the Microsystems Technology Laboratory, as well as Harvard's Center for Nanoscale Systems. Both formal and informal collaborations with leading research groups from around the world are important to necstlab's contributions.

In fall 2014, the group is scheduled to move into new laboratory facilities in Building 35. Examples of past and current research projects include:

- Biofunctionalized nanoelectromechanical systems (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 three-dimensional MEMS
- Vertically aligned carbon nanotubes (VACNT) characterization and physical properties

The faculty of necstlab includes Brian L. Wardle (director), John Dugundji (emeritus), and visitors Alexandre Ferreira Da Silva and Antonio Miravete.

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 is electric propulsion, in which electrical energy, rather than chemical energy, propels spacecraft. The benefits are many, which is why 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 engines and plumes and their interaction with spacecraft and thruster materials, and numerical and experimental models of magnetic cusped thrusters. 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 electrospray thrusters, including their integration into space missions. In addition to providing efficient propulsion for very small satellites in the 1 kg category (such as CubeSats), these engines will enable distributed propulsion for the control of large space structures, such as deformable mirrors and apertures. The science behind electrosprays is explored as well, mainly on the ionic regime where molecular species are directly evaporated from ionic liquid surfaces. Applications beyond propulsion are also investigated; for example, the use of highly monoenergetic molecular ion beams in focusing columns for materials structuring and characterization at the nanoscale. SPL facilities include a supercomputer cluster where plasma and molecular dynamics codes are routinely executed and a state-of-the-art laboratory that includes five vacuum chambers, a clean-room environment, electron microscopy, materials synthesis capabilities, nanosatellite qualification equipment (vibration/thermal and in-vacuum magnetically levitated CubeSat simulator) and plasma/ion beam diagnostic tools to support ongoing research efforts.

The SPL faculty are professors Paulo Lozano, director, and Manuel Martinez-Sanchez, emeritus.

Space Systems Laboratory

Space Systems Laboratory (SSL) research contributes to the exploration and development of space. 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, AeroAstro student-built instruments and small satellites for exploration and remote sensing, precision optical systems for space telescopes, and microgravity experiments operated aboard the ISS and NASA's reduced gravity aircraft. Research topics focus on space systems and include systems architecting, dynamics and control, active structural control, space power and propulsion, modular space systems design, microsatellite design, real-time embedded systems, and software development.

SSL has a unique facility for space systems research, the synchronized position hold engage and reorient experimental satellites (SPHERES) facility. This facility is used to develop proximity satellite operations, such as inspection, cluster aggregation, collision avoidance, and docking, as well as formation flight. The SPHERES facility consists of three satellites, 20 centimeters in diameter, that have been inside the ISS since May 2006. In 2009, SSL expanded the uses of SPHERES to include STEM outreach through Zero Robotics (http://zerorobotics.mit.edu), which engages high-school and middle-school students in a competition aboard the ISS using SPHERES. A pilot program that began in 2009 with two teams from Idaho has expanded to approximately 100 US and 50 European teams each year. In 2013, finalists were joined by astronauts Barbara Morgan, Gregory Johnson, and Gregory Chamitoff, and by *Ender's Game* director Gavin Hood and special effects supervisor Mattew Buttler as they watched, their code run on the satellites aboard the ISS in real time, by video downlink.

There have been several recent and exciting hardware augmentations to SPHERES. In summer 2013, the University of Maryland Space Power and Propulsion Laboratory, Aurora Flight Sciences, and SSL upgraded the SPHERES facility to include the resonant inductive near-field generation system, which has been used to test electromagnetic formation flight and wireless power transfer through a pair of tuned resonant coils that generate a time-varying magnetic field. The SPHERES-Slosh module was also launched in 2013, in collaboration with the Florida Institute of Technology, and has enabled surveys of fluid slosh behavior in zero gravity. Recently, SSL partnered with the Naval Research Laboratory and Aurora Flight Sciences to work on the Defense Advanced Research Projects Agency Phoenix program for satellite servicing and assembly missions. To this end, universal docking ports and Halos will be launched and operated on the SPHERES ISS facility in fall 2014. The universal docking ports enable active docking and undocking of the satellites creating a rigid assembly; they add fiducial-based vision navigation. The Halo structure enables attachment of up to six electromechanical devices around a single SPHERES satellite, allowing researchers to study complex geometrical system reconfiguration. During the fall 2013 and spring 2014 semesters, the MIT 16.83x senior space systems design capstone class developed a prototype for the integrated navigation sensor platform for EVA control and testing

(INSPECT) program, which added a thermal imager, optical range finder, and control moment gyros to the basic SPHERES plus Halo system.

SSL is also active in the area of nanosatellites, particularly CubeSats. In March 2014, the microsized microwave atmospheric satellite (MicroMAS), a joint effort between SSL students, led by professor Kerri Cahoy, and Lincoln Laboratory staff, led by Dr. Bill Blackwell, was delivered to NanoRacks for launch to the ISS, from which MicroMAS will be deployed in summer 2014. MicroMAS is a dual-spinning three-unit CubeSat hosting a microwave radiometer payload that captures temperature map images of Earth and is important for characterizing hurricanes and tropical storms. SSL will develop the microwave radiometer technology acceleration mission (MiRaTA) to follow MicroMAS. MiRaTA pairs an advanced miniature microwave radiometer with a GPS radio occultation receiver to help improve radiometer calibration; it is sponsored by NASA's Earth Science Technology Office and is scheduled for launch in 2016. SSL students are working with engineers at Aurora Flight Sciences and AeroAstro's Space Propulsion Laboratory on a cluster formation-flight nanosatellite project. SSL students are also engaged with professor Sara Seager and students in MIT's Department of Earth, Atmospheric, and Planetary Sciences (EAPS), engineers at the Draper Laboratory, and NASA Jet Propulsion Laboratory on the novel ExoplanetSat nanosatellite. ExoplanetSat uses a two-stage control system (reaction wheels plus piezo stage) to maintain precise pointing at a target star to obtain exoplanet transit measurements using advanced photometry.

The Wavefront Control Laboratory (WCL), led by Professor Cahoy, is a part of SSL that focuses on precision active optical systems for space applications. WCL students are working on three projects. One is the Deformable Mirror Demonstration Mission (DeMi), which will validate and demonstrate the capabilities of high-actuator-count MEMS deformable mirrors for high-contrast astronomical imaging. The DeMi optical payload will characterize MEMS deformable mirror operation using both a Shack Hartmann wavefront sensor and sensorless wavefront control. The second project is a CubeSat Free Space Optical communications downlink that uses a staged control system with MEMS fast-steering mirrors. The third project is a bistatic laser system for active characterization of the bidirectional reflectance distribution function of space materials. WCL students also are investigating whether or not standard communications satellite components can be used as space weather sensors, and developing algorithms that can predict the onset of space-weather-related anomalies.

SSL is also developing and building the regolith X-ray imaging spectrometer (REXIS) student collaboration instrument. It will be aboard NASA's next New Frontiers mission—the origins, spectral interpretation, resource identification, security regolith explorer, or OSIRIS-REx. OSIRIS-REx is an asteroid sample return mission that is scheduled to be launched in 2016 to visit the near-Earth asteroid Bennu. REXIS is one of five instruments that will be onboard; it is set to use a 2x2 array of Lincoln Laboratory–designed charged-coupled devices to measure the X-ray fluorescence from Bennu. This will allow characterization of the surface of the asteroid and a coded aperture mask to map the spatial distribution of element concentrations in the regolith. Professor Richard Binzel, who holds a joint EAPS–AeroAstro appointment, and Dr. Rebecca Masterson of AeroAstro are leading the project in collaboration with EAPS, the Kavli Institute, and the Harvard College Observatory. REXIS has included the work of more than 50 undergraduate and graduate students and has successfully completed its critical design review. The team is wrapping up the engineering model testing and is on the path to building the flight hardware. The REXIS flight instrument will be delivered to Lockheed Martin for integration on the OSIRIS-REx spacecraft in the summer of 2015.

SSL is directed by Dr. Alvar Saenz Otero, who took over this year from professor David Miller, who is on leave from MIT; he is serving as NASA's chief technologist. Other SSL personnel include professors Kerri Cahoy, Jeffrey Hoffman, Olivier de Weck, and Richard Binzel, and; Dr. Rebecca Masterson, Dr. Danilo Roascio, research specialist Paul Bauer, fiscal officers Suxin Hu and Ngan Kim Le, and administrative assistant Marilyn E. Good. Collaborators include AeroAstro professors Manuel Martinez-Sanchez and Paulo Lozano, and EAPS professor Sara Seager.

System Engineering Research Laboratory

The increasingly complex systems being built today enable us to accomplish tasks that were previously difficult or impossible. At the same time, these systems have changed the nature of accidents and have 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 being challenged by new technology and by the increasing complexity of systems. Software is changing the causes of accidents and the humans who now operate these complex systems have a much more difficult job than simply following pre-defined procedures. Engineering design can no longer be separated from human factors and from the social and organizational surroundings in which systems are designed and operated.

The goal of the Laboratory for Systems Safety Research (LSSR) 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. LSSR has participants from many 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 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

The System Engineering Research Laboratory 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 (TELAMS). They work cooperatively to advance the knowledge and understanding that will help 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 changed laboratory name (it was formerly the 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 to address 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 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 coordinated efforts, both internal and external, TELAMS continues its commitment to leadership in the advancement of the knowledge and capabilities of the materials and structures community through education, original research, and interactions with the community. There has been a broadening of this commitment that is 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.

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. Here are details of a few specific projects.

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 design of practical, near-optimal cooperative localization algorithms. The group is currently validating the algorithms in a realistic network environment through experimentation in the laboratory.

The group 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, omnidirectional wideband antennas to measure wireless channels over a range of 2 to 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 under way to analyze the vast amounts of data collected during an extensive measurement campaign that was completed in early 2009.

Laboratory students are also investigating physical-layer security in large-scale wireless networks. Such security schemes will play increasingly important roles in new paradigms for the guidance, navigation, and control of unmanned aerial vehicle networks. The framework the students 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. 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 members of underrepresented minority groups, 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. Professor Win maintains dynamic collaborations and partnerships with academia and industry, including the University of Bologna and Ferrara in Italy, the University of Lund in Sweden, the University of Oulu in Finland, the National University of Singapore, Nanyang Technological University in Singapore, Draper Laboratory, the Jet Propulsion Laboratory, and the 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 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 included 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, and the aeroelastic dynamics of airport control tower configurations for the Federal Aviation Administration. Somewhat unexpected were the live 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. In its more than 75 years of operations, Wright Brothers Wind Tunnel work has been recorded in hundreds of theses and more than 1,000 technical reports.

Wright Brother Wind Tunnel faculty and staff include Mark Drela and Richard Perdichizzi.

Since opening in September 1938, the Wright Brothers Wind Tunnel has played a major role in the development of aerospace, civil engineering and architectural systems.

Degree Programs

The bachelor of science (SB) degree program 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 their coursework to become practicing engineers upon receipt of the undergraduate degree, to continue on to graduate studies in any of the specialties, or to pursue fields outside engineering.

Since academic year 2013, the 16-1 and 16-2 degrees have been combined into a single aerospace engineering degree program (16 – Aerospace Engineering). The combined program retains the previous deep emphasis on the fundamentals and provides strong integration within the overarching "conceive, design, implement, operate" context. In addition, an informal option in aerospace information technology exists for those students who select at least three professional area subjects from a designated list.

The Department of Aeronautics and Astronautics also offers a relatively new, more flexible program—Course 16-ENG with an emphasis on 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. The flexible degree program also builds on the department's strength in collaborative, multidisciplinary problem solving. In 2014, the 16-ENG degree program offered concentrations in aerospace software engineering, autonomous systems, communications, embedded systems and networks, computational engineering, computational sustainability, energy, engineering management, environment, space exploration, and transportation.

The skills and attributes emphasized in all AeroAstro programs go beyond the formal classroom curriculum and include modeling, design, the ability for self-education, 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 the departmental subjects through examples set by the faculty, through the disciplinary content, and through the ability 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	13–14
Total Graduate Student Body	**226**	**236**	**226**	**226**	**229**	**246**	**241**
SM**	146	148	130	111	121	125	117
PhD***	80	88	96	115	108	121	124
Minority							
SM	8	8	9	7	9	12	13
PhD	5	6	4	6	5	6	5
Female							
SM	29	32	30	22	21	23	23
PhD	19	23	17	20	16	22	26

*Numbers based on fifth-week enrollment data.

** 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

	04–05	05–06	06–07	07–08	08–09	09–10	10–11	11–12	12–13	13–14
Sophomores	64	65	65	57	**74**	**57**	**51**	**45**	**66**	**71**
Juniors	59	52	60	66	**55**	**65**	**47**	**46**	**43**	**53**
Seniors	65	76	56	66	**62**	**58**	**68**	**47**	**45**	**44**
Totals	**188**	**196**	**181**	**189**	**191**	**180**	**166**	**138**	**154**	**168**
% Women	30%	26%	31%	30	30%	34%	29%	31%	37%	36%
% Underrepresented minorities	27%	25%	19%	14%	32%	40%	28%	38%	30%	31.5%

* Data based on the Registrar's Fall Fifth Week Enrollment Reports.

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