Department of Aeronautics and Astronautics

The MIT Department of Aeronautics and Astronautics (AeroAstro) is a vibrant community of uniquely talented faculty, students, alumni, and staff committed to excellence. We eagerly anticipate and embrace the grand challenges of today and tomorrow, as we have throughout our more than 100 years of dedication to aerospace research and education.

AeroAstro is one of America's oldest and most celebrated aerospace engineering departments, with undergraduate and graduate programs consistently ranked among the best by *U.S. News & World Report*. While 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 medium size.

The department's undergraduate student body is constant at approximately 175, while our graduate program serves about 250 master's and PhD degree candidates. Both programs are among the most competitive in the nation; in fact, the department retains its number one ranking among the country's undergraduate and graduate aerospace engineering programs.

At the end of AY2016, the department's faculty count stood at 36.5 (including eight core and three affiliate faculty from the MIT Institute for Data, Systems, and Society). Jayant Sabnis, a former vice president of Pratt & Whitney, joined the department as a senior lecturer in March 2016.

The department was visited by the Corporation Visiting Committee for Aeronautics and Astronautics in September 2015. Feedback from the visiting committee was positive. Suggestions included devising a funding strategy for the aging Wright Brothers Wind Tunnel (WBWT), tweaking the SB/SM curriculum to increase opportunities for hands-on experiences in the freshman and sophomore years, and identifying novel ways in which to increase sophomore enrollment.

Apollo 13 commander Jim Lovell's April 28, 2016, visit to AeroAstro drew a capacity crowd to hear him recount his lunar mission's "successful failure." Lovell is pictured here taking questions from students in the AeroAstro hangar at a reception prior to the talk. (Photo: William Litant/MIT)

One of the most anticipated events of the academic year was the visit of retired United States Navy captain and former astronaut Jim Lovell, who spoke on "A Successful Failure." Captain Lovell addressed a standing-room-only crowd in Building 10-250, sharing details of the ill-fated Apollo 13 mission of which he was commander. Later in the day, Captain Lovell spoke once more, fielding student questions in a Q&A session at the American Institute of Aeronautics and Astronautics (AIAA) student-faculty dinner.

After a year's hiatus, the department once again hosted the Women in Aerospace Symposium. The 2016 event was different from previous years in that Stanford University's Department of Aeronautics and Astronautics was a co-sponsor, sending faculty to represent the school and participate on expert panels. Another deviation from prior symposia was the competitive nature of the program, wherein doctoral students and postdoctoral researchers from across the globe submitted both CVs and abstracts, with the most promising chosen to present their work here in Cambridge. With 23 invited presenters and keynote presentations by Dava Newman, deputy administrator of the National Aeronautics and Space Administration (NASA), and Radhika Nagpal, Fred Kavli Professor of Computer Science at Harvard, the two-day event was extraordinarily well received.

An AeroAstro student team led by Professor Kerri Cahoy has developed KitCube, a backpack-sized satellite proving to be a top contender in the NASA CubeQuest Challenge, a competition offering the winners' project a ride aboard the Exploration Mission-1. Placing second in the first two competitions, Team KitCube has fared extraordinarily well in terms of not only the CubeQuest Challenge but also in raising almost $125,000 through crowdfunding.

Visitors to the April 2016 MIT open house learn about aviation's environmental impact from Laboratory for Aviation and the Environment graduate students Cooper Hennick (left) and Akshat Agarwal. (Photo: William Litant/MIT)

On April 23, the department hosted yet another successful open house. This year's event—part of the celebration of MIT's centennial in Cambridge—featured a variety of activities, including lab tours, flight simulators, vehicle demonstrations, displays, and hands-on activities for children such as a parachute build/egg drop, air-launched rockets, and a paper airplane competition. Hundreds visited the department as both labs and student groups put their best foot forward.

Promoting Faculty Excellence

The AeroAstro faculty includes Hamsa Balakrishnan, Steven Barrett, Kerri Cahoy, Edward Crawley (on leave while serving as president of the Skolkovo Institute of Science and Technology), David Darmofal, Olivier de Weck, Mark Drela, Emilio Frazzoli, Edward Greitzer, Steven Hall, R. John Hansman, Wesley Harris, Daniel Hastings (on leave as director of the Singapore-MIT Alliance for Research and Technology), Woody Hoburg, Jonathan How, Sertac Karaman, Paul Lagacé, Nancy Leveson, Paulo Lozano, Youssef Marzouk, David Miller (on leave while serving as NASA chief technologist), David Mindell (0.5 full-time equivalent [FTE], dual appointment with the Program in Science, Technology, and Society), Eytan Modiano, Dava Newman (on leave while serving as NASA deputy administrator), Jaime Peraire, Raul Radovitzky, Nicholas Roy, Julie Shah, Zoltan Spakovszky, Leia Stirling, Ian Waitz (in a full-time administrative role as dean of the School of Engineering), Qiqi Wang, Brian Wardle, Sheila Widnall, Karen Willcox, Brian Williams, and Moe Win. Professor Peraire is the head of the department; Professor Modiano is associate department head. After a rigorous search, the department has hired Carmen Guerra-Garcia as an assistant professor; however, Carmen will not be joining the faculty until September 2017 (spending a year at Boeing in Madrid).

Department faculty members continue to meet weekly, providing a forum for research presentations, departmental updates, and general discussion. The department welcomes individuals from other units across campus to present at these meetings as well. Dean Waitz also takes the opportunity to visit the department each semester with updates.

Department leaders continue to hold meetings with junior faculty on a regular basis. These meetings provide a forum for young faculty to express concerns, share comments, and seek the support of the leadership. In turn, Professors Peraire and Modiano are given the opportunity to assess how well junior faculty are acclimating to the department and to determine whether any problems that might otherwise go unnoticed have arisen.

Promotions

- Kerri Cahoy was promoted to associate professor without tenure, effective July 1, 2016.
- Sertac Karaman was promoted to associate professor without tenure, effective July 1, 2016.
- Steven Barrett was promoted to associate professor with tenure, effective July 1, 2016.
- Youssef Marzouk was promoted to associate professor with tenure, effective July 1, 2016.

Recognition

- Professor Peraire received the Catalan Civil Engineers Association's Ildefons Cerda Medal for "his exceptional international academic, scientific, and professional career." He was also presented the T.J.R. Hughes Medal by the US Association for Computational Mechanics.
- Professor Emeritus and Pratt & Whitney vice president Alan Epstein won the Aircraft Engine Technology Award from the American Society of Mechanical Engineering.
- Professor Willcox was awarded a First in the World Development Grant by the Department of Education. Also, Willcox received the 2016 Distinguished Alumni Award from the University of Auckland.
- Professor How was elected a fellow of the American Institute of Aeronautics and Astronautics.
- Professor Leveson received the 2016 Vladmir Syromyatnikov Safety-by-Design Award from the International Association for the Advancement of Space Safety.
- Harvard University accepted Professor Shah as a Radcliffe Fellow for AY2017.
- Professor Barrett and the Laboratory for Aviation and the Environment were awarded "Best Article of 2015" by Environmental Research Letters for their work on the study linking Volkswagen emissions to premature deaths.
- Professor Harris won the AIAA Undergraduate Advising Award, which is given by the AIAA Student Chapter to a faculty or staff member who has demonstrated excellence in serving as an academic or 16.621/16.622 (Experimental Projects Lab I/II) advisor and has had a positive impact on a student's time in AeroAstro.
- Professor Radovitzky received the AIAA Undergraduate Teaching Award, given by the AIAA Student Chapter to a faculty or staff member who exemplifies the role of a "great teacher."

Promoting Excellence in Graduate Education

AeroAstro received 643 applications for admission to its graduate programs, admitting 94 applicants (an admission rate of 15%). Of the 94 students admitted, 65 enrolled, for a yield of 69%. Women accounted for 15% of the entering class, while 6% of the class met the criteria for underrepresented minority groups.

The department's graduate program was again ranked first in the country by *U.S. News & World Report*. During the period September 2015 through June 2016, the department graduated 28 PhD and 60 SM students.

Continuing a 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. Also, 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

- Koki Ho received the 2015 Luigi G. Napolitano Award, presented annually by the International Astronautical Federation to an under-30 scientist who has contributed significantly to aerospace science.
- AeroAstro grad students Luke Johnson and Brett Lopez were part of an MIT team that captured first place in the IEEE (Institute of Electrical and Electronics Engineers) Control System Society's 2015 Video Contest.
- The AeroAstro Graduate Teaching Assistantship Award, which is given to a graduate teaching assistant who has demonstrated conspicuous dedication and skill in helping fulfill an undergraduate or graduate subject's educational objectives, was presented to Mohammad Islam and Roedolph Opperman.
- The Rene H. Miller Prize for Excellence in Systems Engineering (open to both undergraduate and graduate students), which is given to the student who has done the best piece of work in systems engineering in the department, was awarded to Anne Marinan.

Promoting Excellence in Undergraduate Education

The department remains strongly committed to promoting undergraduate research, hiring a number of students through the Undergraduate Research Opportunities Program (UROP). In AY2016, AeroAstro hired 250 UROP students, of whom 35 (14%) were freshmen. During summer 2016, 23 of the department's 42 UROP students (55%) were rising sophomores.

In AY2016, AeroAstro teamed with the Department of Electrical Engineering and Computer Science to offer advanced undergraduate research opportunities to its upperclassmen; the two-pronged SuperUROP program involves yearlong coursework and research under the direct supervision of a faculty member. Students spend approximately 10 hours per week working in a lab on an approved project and attend a weekly lecture featuring speakers from academia and industry, for which they are given both a stipend and course credit. Sixteen AeroAstro juniors and seniors successfully completed the SuperUROP program during the department's first year of engagement.

The department continues to require reflective memos from all undergraduate instructors as a means of promoting continuous improvements in faculty teaching performance. Following the submission of a reflective memo, the associate department head meets with the instructor to review what has happened in the past term and to discuss ways in which she or he may improve performance.

The AeroAstro-sponsored MIT Rocket Team placed first in the 2015 International Rocket Engineering Competition's "Basic" class, besting 36 other university teams from seven countries

Recognition

- Apollo Program Prize, given to the AeroAstro student who conducts the best undergraduate research project on the topic of humans in space: Johannes Norheim; Aaron Ashley and Guillermo Bautista
- Andrew J. Morsa Prize, given for demonstration of ingenuity and initiative in the application of computers to the field of aeronautics and astronautics: Joseph Kusters and Derek Barnes
- Thomas B. Sheridan Prize, awarded to the AeroAstro or mechanical engineering student or students whose research or design project best exemplifies creativity or improvement in human-machine integration or cooperation: Evie Kyritsis and Margaret Reagan
- Leaders for Manufacturing Undergraduate Prize, presented to a student team that has demonstrated excellence and/or innovation in addressing the interaction between manufacturing and engineering during the execution of their project: Julie Crowley Farenga; Raichelle Aniceto and Rachel Weinberg
- Yvnge Raustein Award, given to a unified engineering student who best exemplifies the spirit of Yngve Raustein and to recognize significant achievement in unified engineering: Maya Nasr
- Admiral Luis De Florez Prize, awarded for "original thinking or ingenuity": Andrew Liotta and Kelly O'Brien
- James Means Award for Excellence in Flight Vehicle Engineering: Patrick Lowe
- James Means Award for Excellence in Space Systems Engineering: Eduardo Maristany and Timothy "Curtis" Shoyer
- SuperUROP Research Project Award, presented to a student for an outstanding advanced UROP project: Michael Burton

- 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: Michael Burton, Andrew Liotta, and Martin York

The AeroAstro-sponsored MIT Rocket Team placed first in the 2015 International Rocket Engineering Competition's "Basic" class, besting 36 other university teams from seven countries.

Improving AeroAstro's Physical Space

The Building 31 renovation project is progressing well and is expected to be completed by the fall 2017 term. The finished project will include a newly constructed 3,200-square-foot high-bay space with 24-foot-tall ceilings and a motion capture system to test unmanned autonomous flying vehicles. Additionally, the building will be connected to Building 37 via a bridge on the third floor and will include a 4,800-square-foot outdoor deck that will allow outdoor flying tests. The newly renovated building will also house Beaver Works 2.0, a flexible maker space that will be shared by Lincoln Laboratory and the department.

Building 31's new high-bay space will be home to the Center for Autonomous Systems, a place where AeroAstro researchers can conduct research involving flying robotic aerial systems. (William Litant/MIT photograph)

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 [and] urgently needs to be upgraded."

While the renovation of Building 31 will improve the conditions of the Gas Turbine Laboratory and create both student offices and space for autonomy research, issues with the Wright Brothers Wind Tunnel persist. Used by every student who matriculates in the department, the iconic WBWT is often down for repairs, interfering with not only research but also education. While we have completed a study of Building 17 (WBWT) and have plans to take this on as our next large capital project, locating funding will require that we redouble our development efforts.

Small renovations have recently taken place in Buildings 35 and 37, resulting in new labs for several faculty as well as additional graduate student clusters. Until fall 2017, quantity and quality of space will remain a constant challenge for the department. In the meantime, we continue to make improvements in the care and maintenance of existing space. Fundraising to support renovation of space and facilities remains a top priority.

Resource Development

In 2015–2016, the department focused on obtaining additional funds to close out the renovation of Building 31 and support people and programs across AeroAstro. Efforts have begun to explore the viability of a fundraising plan to rehabilitate or replace the Wright Brothers Wind Tunnel. Various student teams also ran successful fundraising campaigns on the new crowdfunding site hosted by the MIT Alumni Association, including the MIT KitCube Lunar Orbiter and MIT Flugtag teams.

Prospect visits led by Mark Veligor and department head Jaime Peraire took place in Washington, DC; Los Angeles; Seattle; and San Francisco as well as on campus; many AeroAstro professors participated in these visits, including Paulo Lozano, Julie Shah, Hamsa Balakrishnan, Steven Barrett, and Nick Roy. We are currently working with the Alumni Association and the Office of Resource Development on 2016–2017 West Coast events and are beginning to plan the celebration on campus to reopen Building 31 in fall 2017.

Outreach

In January 2016, the department once again took 40 sophomore students on an educational trip to the West Coast for visits to Boeing (Renton and Everett facilities), Virgin Galactic, the Lockheed Martin Skunk Works, the Jet Propulsion Laboratory, SpaceX, and Northrop Grumman Aerospace. Students were afforded the opportunity to meet with alumni, to talk to the very people doing the jobs they dream of, to ask questions, and to whet their appetites for aerospace. We will be continuing this tradition in future years.

The May 24-26, 2016 Women in Aerospace Symposium, presented by AeroAstro in conjunction with Stanford University, offered outstanding women doctoral and postdoctoral researchers a unique opportunity to present their work to, and network with, their colleagues, university faculty, and industry/government professionals. (William Litant/MIT photograph)

The Women in Aerospace Symposium returned to campus in May 2016, when MIT's Department of Aeronautics and Astronautics teamed with its namesake at Stanford to host a two-day event. Twenty-three women attended this year's symposium, at which the keynote speakers were Dava Newman (NASA deputy administrator) and Radhika

Nagpal (Fred Kavli Professor of Computer Science at Harvard University). It is the intention that Stanford will host next year's event.

School Awards

- Anthony Zolnik was presented the Infinite Mile Award, given to individuals whose work is of the highest quality and who stand out because of their high level of commitment and the enormous energy and enthusiasm they bring to their work.
- Rebecca Masterson received the Infinite Kilometer Award, established by the MIT School of Science to highlight and reward the extraordinary but often underrecognized work of research staff and postdocs.

Departmental Awards

- Elizabeth Zotos received the Wings Award, which recognizes an individual support staff member in AeroAstro for excellence.
- Jacques Matthieu and Jei Lei Freeman received the Spirit of XVI Award, which recognizes an AeroAstro individual or team 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 presented to Anne Maynard.
- The Simon Award, a new award given for exceptional contributions to the department, was presented to Jimmy Letendre, Dave Robertson, and Todd Billings.

Research

The department's total research expenditures (adjusted for dual appointments) for FY2014, FY2015, and FY2016 were $31.167 million, $28.058 million, and $29.292 million, respectively.

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

Aerospace Computational Design Laboratory

The mission of the Aerospace Computational Design Laboratory (ACDL) 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. The lab has a long-standing interest in 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.

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 solutions to stochastic differential equations, solutions to large-scale statistical inverse problems, nonlinear filtering in partial differential equations (PDEs), 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 have 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. The research staff includes 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 (UAVs); sensor network design; and robust, adaptive, and nonlinear control. A key aspect of ACL is RAVEN (Real-time indoor Autonomous Vehicle test ENvironment), a unique experimental facility that uses a motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and aircraft and robust coordination algorithms for multiple vehicles; the facility also has a ground projection system that enables real-time animation of the planning environment, beliefs, uncertainties, vehicle intentions, predicted behaviors (e.g., trajectories), and learning algorithm confidence intervals. The following are examples of recent ACL research.

Robust Planning in Uncertain Environments: ACL developed 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 networks, 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 multiyear 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 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 resulting from 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 (MDPs) and partially observable MDPs 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 inaccacurate 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 mission of the Aerospace Robotics and Embedded Systems group 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. Examples of current research areas are as follows.

Autonomy and Future Urban Mobility: Autonomous, self-driving cars are no longer science fiction but 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 analyses of the socioeconomic impact of such technology. Recent work includes the following.

- Affordable autonomy: can we design safe and reliable self-driving vehicles at a cost that makes them affordable for the general public? The group's demonstration vehicles at the Singapore-*MIT* Alliance for Research and Technology were developed with less than $30,000 worth of computers and sensors.

- Provable safety: how do we make sure that the vehicle will behave safely and respect all of 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 impact urban mobility in the future? The group envisions fleets of shared self-driving vehicles, develop algorithms for their sizing and operations, and analyze 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. 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 offroad driving.

Multi-Agent Systems: Large, heterogeneous groups of mobile vehicles, such as UAVs 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 designing distributed algorithms to ensure provably efficient and safe execution of assigned tasks but also understanding 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 saturates, new approaches are necessary to increase the safety, efficiency, and environmental sustainability of transportation networks. The group's research in this area concentrates on the exploitation of real-time information availability through wireless communications among vehicles, and with existing infrastructure, to achieve this goal.

Emilio Frazzoli directs the Aerospace Robotics and Embedded Systems group.

Autonomous Systems Laboratory

The Autonomous Systems Laboratory is a virtual lab led by Brian Williams and Nicholas Roy. Williams's group, the Model-based Embedded and Robotics Group (MERS), 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 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 autonomously 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. (A video is available at http://www.csail.mit.edu/videoarchive/research/robo/auv-planning.)

- 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 the original goals no longer can 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 innovative vehicles, one must be trained as a certified pilot, thus limiting the population that can benefit from this innovative concept. In collaboration with Boeing, MERS has demonstrated in simulation the concept of an autonomous personal air vehicle in which passengers interact with the vehicle in the same manner they interact today with a taxi driver. (A video is available at http://www.csail.mit.edu/videoarchive/research/robo/personal-aerial-transportation.)
- 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 concepts to control the JPL ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) robot, a six-legged/wheeled lunar rover that performs heavy lifting and manipulation tasks by using its legs as arms. (A video is available at http://www.csail.mit.edu/videoarchive/research/robo/athlete-mers.)

Communications and Networking Research Group

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

The group is working on a wide range of projects in the area of communication networks and systems, with applications 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 local area networks. While multi-hop wireless networks can be deployed, current protocols typically result in extremely poor performance for even moderate-sized networks. Wireless mesh networks have emerged as a solution for providing last-mile Internet access. However, hindering their success is our relative lack of understanding of how to effectively control wireless networks, especially in the context of advanced physical layer models, realistic models for channel interference, distributed operations, and interfaces with the wired infrastructure (e.g., the Internet). The group 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 attacks. 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 mission of the Gas Turbine Laboratory is to advance the state of the art in fluid machinery for power and propulsion. The research is focused on advanced propulsion systems, energy conversion, and power, with activities in the 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. Current research projects include the following:

- A unified approach for vaned diffuser design in advanced 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
- 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
- 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
- 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
- Investigation of surface waviness effects on compressor performance

The faculty and research staff of the Gas Turbine Laboratory include David Darmofal, Fredric Ehrich, Alan Epstein (emeritus), Edward Greitzer, Claudio Lettieri, Zoltan Spakovszky (director), Choon Tan, Neil Titchener, and Alejandra Uranga.

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

Airline operations are also undergoing major transformations. Airline management, airport security, air transportation economics, fleet scheduling, traffic flow management, and airport facilities development represent areas of great interest to the MIT faculty and are of vital importance to international air transportation. ICAT is a physical and intellectual home for these activities. ICAT and its predecessors, the Aeronautical Systems Laboratory and the 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 the 1990s as the Aero-Environmental Research Laboratory by Ian A. Waitz, now dean of the MIT School of Engineering.

One of the aviation industry's defining challenges is addressing aviation's environmental impact in terms of noise, air quality, and climate change. LAE's goal is to align the trajectory of aerospace technology and policy development with the need to mitigate these impacts. It does so by increasing understanding of the environmental effects of aviation; by developing and assessing fuel-based, operational, and technological mitigation approaches; and by disseminating knowledge and tools. LAE 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 impact. 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 options such as liquefied natural gas, which would require modifications to aircraft and infrastructure. Environmental metrics considered include life-cycle greenhouse gas emissions, land requirements, and water consumption. LAE researchers are also estimating trade-offs among different metrics and usages 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 for modeling and evaluation of emissions and their impacts throughout the troposphere and stratosphere in a unified fashion. LAE has also recently released a new global emissions data set for civil aviation emissions that represents the most current estimate of emissions publicly available. It is widely used by researchers worldwide, in areas including 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 usage for road transportation.

The 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.

Dating to 1939, LIDS has been at the forefront of major methodological developments relevant to diverse areas of national and worldwide importance, such as telecommunications, information technology, the automotive industry, energy, defense, and human health. Building on past innovation and bolstered by a collaborative atmosphere, LIDS members 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 lab and with the larger MIT community. AeroAstro faculty affiliated with the laboratory are Emilio Frazzoli, Jonathan How, Eytan Modiano, and Moe Win.

Learning Laboratory

The AeroAstro Learning Laboratory, located in Building 33, promotes student learning by providing an environment for hands-on activities that span our conceive-design-implement-operate educational paradigm. The Learning 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 learn about program reviews and management.
- 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, the Instrumentation Laboratory, the Mechanical Projects Area, the 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 highbay 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 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.

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

Aboard a parabolic aircraft flight, Man Vehicle Lab grad student Pierre Bertrand conducts experiments in reduced-gravity astronaut maneuvering. (Novespace/CNES photograph)

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, on the Mir Space Station, and on many parabolic flights and has developed experiments for the International Space Station (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 General Electric 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.

Research sponsors include NASA, the National Space Biomedical Research Institute (NSBRI), the National Science Foundation (NSF), the Office of Naval Research (ONR), the Federal Aviation Administration, the Federal Railroad Administration, Draper Laboratory, the Center for Integration of Medicine and Innovative Technology, the Deshpande Center, and the MIT Portugal Program. The laboratory also collaborates with the Volpe Transportation Research Center, Massachusetts General Hospital, and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

The MVL faculty includes Jeffrey Hoffman, director; Laurence Young; Chuck Oman; 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. MVL also serves as the office of the director for the NSBRI-sponsored Harvard-MIT Division of Health Sciences and Technology Graduate Program in Bioastronautics (Young) and the Massachusetts Space Grant Consortium (Hoffman).

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 at the forefront of materials and structures understanding, with research contributions in both science and engineering. Applications of interest include enhanced aerospace advanced composites, multifunctional attributes of structures such as damage sensing, and microfabricated (microelectromechanical systems [MEMS]) topics. The necstlab group has interests that range from fundamental materials synthesis questions to structural applications of both hybrid and traditional materials. Much of the group's work supports the efforts of the Nano-Engineered Composite Aerospace Structures (NECST) Consortium, an aerospace industry–supported research initiative that seeks to develop the underlying understanding needed to create enhanced-performance advanced composites using nanotechnology. Beyond the NECST Consortium members, necstlab research is supported directly or through collaborations with industry, the Air Force Office of Scientific Research, the Army Research Office, NASA, the National Institute of Standards and Technology, NSF, ONR, and others.

The necstlab group also 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 labs 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. Collaborations with leading research groups from around the world are important to the contributions of necstlab. In fall 2014, the group moved into new laboratory space 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 nanoengineered bulk materials, including damage sensing and detection
- Nanomanufacturing
- 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
- Vertically aligned carbon nanotube characterization and physical properties

The necstlab faculty includes Brian L. Wardle, director; John Dugundji, professor emeritus; and visitor Antonio Miravete.

Space Propulsion Laboratory

The Space Propulsion Laboratory (SPL) studies and develops systems for increasing the performance and reducing the costs of space propulsion and related technologies. A major area of interest to the lab is electric propulsion, in which electrical rather than chemical energy propels spacecraft. The benefits are numerous, 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 also has a significant role in designing and building microfabricated 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. A recent line of research is focused on the favorable scaling potential of electrospray thrusters for applications in power-intensive missions. SPL has delivered flight hardware to test the first electrospray thrusters in space in CubeSats. The science behind electrosprays is explored as well, mainly on the ionic regime where molecular species are directly evaporated from ionic liquid surfaces. Also, applications beyond propulsion are investigated, including the use of highly monoenergetic molecular ion beams in focusing columns for materials structuring and characterization at the nano scale and applications in vacuum technology. The SPL facilities include a computer cluster where plasma and molecular dynamics codes are routinely executed and a state-of-the-art laboratory with five vacuum chambers, a clean-room environment, an electron microscope, materials synthesis capabilities, nanosatellite qualification equipment (a vibration/thermal and in-vacuum magnetically levitated CubeSat simulator), plasma/ion beam diagnostic tools to support ongoing research efforts, and a laser micromachining facility.

The SPL faculty includes Paulo Lozano, director, and Manuel Martinez-Sanchez, professor emeritus.

Space Systems Laboratory

Research in the Space Systems Laboratory (SSL) 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 the NASA reduced-gravity aircraft. Research topics focus on space systems and include dynamics, guidance, and control; active structural control; space power and propulsion; modular space systems design; micro-satellite design; real-time embedded systems; software development; and systems architecting.

SSL has a unique facility for space systems research, the Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES). The SPHERES facility is used to develop proximity satellite operations such as inspection, cluster aggregation, collision avoidance and docking, and formation flight. The facility consists of three satellites 20 centimeters in diameter that have been inside the International Space Station since May 2006. SSL uses SPHERES to conduct STEM (science, technology, engineering, and mathematics) outreach through an exciting program called Zero Robotics, which engages high school and middle school students in a competition aboard the ISS. It has expanded to over 100 US and 50 European teams annually. For the 2014 competition, finalists were joined at MIT by Dante Lauretta, PI of the Osirix REX Mission and at ESA ESTEC by Matthew Taylor, Project Scientist of the Rosetta mission, as guest speakers. MIT alum and retired NASA Astronaut Catherine "Cady" Coleman hosted the students at MIT while Astronaut Paolo Nespoli, from the Italian Space Agency hosted the students at ESTEC. The competition was run aboard the ISS by three crewmembers: Cosmonaut Elena Serova from Russia, Astronaut Samantha Cristoforetti from Italy, and Barry "Butch" Wilmore from the USA. For the first time teams from Russia and Mexico also participated in this growing competition

There have been several recent and exciting hardware augmentations to SPHERES. In October 2012, the 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. VERTIGO uses vision-based navigation and mapping algorithms through a stereo camera system and an upgraded processor. In

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; this module has enabled surveys of fluid slosh behavior in zero gravity.

Recently, SSL partnered with the Naval Research Laboratory and Aurora Flight Sciences in work on the Defense Advanced Research Projects Agency Phoenix program for satellite servicing and assembly missions. To this end, a cadre of universal docking ports and halos have been launched and operated on the SPHERES ISS facility. The universal docking ports enable active docking and undocking of satellites and 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. Also, the 16.83x Space Systems Engineering senior capstone class has developed a prototype for the INSPECT (Integrated Navigation Sensor Platform for EVA Control and Testing) program, adding a thermal imager, optical range finder, and control moment gyros to the ground SPHERES 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 was 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 a follow-on to MicroMAS called the Microwave Radiometer Technology Acceleration mission (MiRaTA), which pairs an advanced miniature microwave radiometer with a GPS radio occultation receiver to help improve radiometer calibration. MiRaTA is sponsored by the NASA Earth Science Technology Office and scheduled for a 2016 launch. SSL students are working with engineers at Aurora Flight Sciences and the AeroAstro Space Propulsion Laboratory on a cluster formation-flight nanosatellite project. SSL students are also engaged with Professor Sara Seager and students in the MIT Department of Earth, Atmospheric, and Planetary Sciences (EAPS); engineers at Draper Laboratory; and NASA's Jet Propulsion Laboratory on the novel ExoplanetSat nanosatellite, which uses a two-stage control system (reaction wheels plus piezo stage) to maintain precise pointing at a target star as a means of obtaining exoplanet transit measurements via advanced photometry.

The Wavefront Control Laboratory (WCL), led by 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 operations 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 they are developing algorithms that can predict the onset of space-weather-related anomalies.

SSL is also developing and building the REXIS (REgolith X-ray Imaging Spectrometer) student collaboration instrument, which will be aboard OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security Regolith Explorer), NASA's next New Frontiers mission. OSIRIS-REx is an asteroid sample return mission that will launch in 2016 and visit the near-Earth asteroid Bennu. REXIS, one of five instruments onboard, uses a 2 × 2 array of Lincoln Laboratory–designed charged-coupled devices to measure the X-ray fluorescence from Bennu, which will allow characterization of the surface of the asteroid among the major meteorite groups as well as a coded aperture mask to map the spatial distribution of element concentrations in the regolith. Professor Richard Binzel, who maintains a joint appointment in EAPS and AeroAstro, and Dr. Rebecca Masterson 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 the flight hardware build. The REXIS flight instrument has been delivered to Lockheed Martin for integration onto the OSIRIS-REx spacecraft.

SSL is being directed by Alvar Saenz Otero while David W. Miller is on leave from MIT as NASA chief technologist. Kerri Cahoy, Jeffrey Hoffman, Olivier de Weck, and Richard Binzel participate in SSL projects. Rebecca Masterson manages REXIS, and Danilo Roascio leads the SPHERES team. The group is supported by research specialist Paul Bauer, fiscal officers Suxin Hu and Ngan Kim Le, and administrative assistant Marilyn E. Good. Collaborators include Manuel Martinez-Sanchez and Paulo Lozano from AeroAstro and Sara Seager from EAPS.

Space Telecommunications, Radiation, and Astronomy Laboratory

The Space Telecommunications, Radiation, and Astronomy Laboratory (STAR Lab) is affiliated with the Space Systems Laboratory. It focuses on developing instruments and platforms that enable weather sensing on Earth and other planets, including exoplanets, as well as monitoring "space weather"—the highly energetic flow of radiation, or charged particles, constantly streaming toward Earth from the sun. In addition to the flight CubeSat weather sensing projects (MicroMAS and MiRaTA) and work to autonomously optimize the return on spacecraft scientific observation given constrained resources, STAR Lab projects also involve the use of active optical elements, sensing, and tracking systems.

Nanosatellite Optical Downlink Experiment (NODE): NODE is a miniaturized laser communication module for small satellites that incorporates commercial off-the-shelf components, including a MEMS fast-steering mirror for fine pointing, on standard three-axis stabilized spacecraft to achieve free space optical data rates of better than 50 Mbps when downlinking from low Earth orbit to amateur-astronomy-class 30-cm telescope ground stations. The lab is also developing an atmospheric sensor that overlaps with the NODE configuration.

Direct Imaging of Exoplanets: The STAR Lab is involved in mission design and technology demonstration efforts toward direct imaging of exoplanets, a method wherein a space telescope equipped with an occulter is used to image planets around other stars by blocking out (occulting) the parent star and measuring the spectra of the faint exoplanets orbiting it. The spectra are used to tell us about the atmosphere and weather on the exoplanets, as well as to offer indications about life and habitability. One demonstration mission, the Deformable Mirror Demonstration Mission, involves looking at bright stars and testing a MEMS deformable mirror on a 3U CubeSat using a miniaturized Shack Hartmann wavefront sensor. The STAR Lab also collaborates with students in EAPS and staff at the NASA Ames Research Center and Space Telescope Science Institute to do modeling of the retrieved atmospheric spectra.

Space Weather Sensing: In collaboration with the Department of Nuclear Science and Engineering, the STAR Lab is helping to develop miniaturized radiation sensors for satellites that can provide more information about the particle types and energies that affect our orbiting assets than a simple dosimeter can. This effort complements work being done to analyze commercial operator satellite telemetry and anomaly databases to understand the sensitivity of spacecraft and components to space weather events and develop new spacecraft and system health monitoring algorithms.

The STAR Lab is directed by Kerri Cahoy.

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 being challenged by the introduction of new technology and the increasing complexity of the systems we are attempting to build. Software is changing the causes of accidents, and the humans operating these systems have a much more difficult job than simply following predefined 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 goal of the System Engineering Research Laboratory 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 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, unmanned aircraft, air traffic control), spacecraft, medical devices and health care, automobiles, 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 in safety
- Managing and operating safety-critical systems

Recently we have discovered that our safety techniques are also effective for security, and we are now involved in cyber security and physical (nuclear) security in work for the Department of Defense, the Federal Aviation Administration, and the Department of Energy.

The System Engineering Research Laboratory is directed by Nancy Leveson. John Thomas is an affiliated research engineer.

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.

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

- Composite tubular structural and laminate failures
- MEMS-scale mechanical energy harvesting modeling, design, and testing
- MEMS device modeling and testing, including bioNEMS/MEMS
- Structural health monitoring system development and durability assessment
- Thermostructural design, manufacture, and testing of composite thin films and associated fundamental mechanical and microstructural characterization
- Continued efforts in addressing the role 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 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, testing at low and high temperatures, and testing in hostile and other controlled environments. There are facilities for microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization. This includes ties to the ability for computer microtomography.

With its linked and coordinated efforts, both internal and external, the laboratory continues its commitment to leadership in the advancement of the knowledge and capabilities of the materials and structures community through education of students, original research, and interactions with the community. There has been a broadening of this commitment consistent with the broadening of the interest areas in the laboratory. In all of 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.

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

Wireless Communication and Network Sciences Laboratory

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

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

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

The laboratory'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 unmanned aerial vehicle networks. The framework they have developed introduces the notion of a secure communications graph, which captures the information-theoretically secure links that can be established in a wireless network. They have characterized the s-graph in terms of local and global connectivity, as well as the secrecy capacity of connections. They also proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and sectorized transmission. Lastly, they analyzed the capability for secure communication in the presence of colluding eavesdroppers.

To support 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 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 Mitsubishi Electric Research Laboratories.

Moe Win directs the Wireless Communication and Network Sciences Laboratory.

Wright Brothers Wind Tunnel

Since its opening in September 1938, the Wright Brothers Wind Tunnel has played a major role in the development of aerospace, civil engineering, and architectural systems. In recent years, faculty research interests generated long-range studies of unsteady airfoil flow fields, jet engine inlet-vortex behavior, aeroelastic tests of unducted propeller fans, and panel methods for tunnel wall interaction effects. Industrial testing has ranged over auxiliary propulsion burner units, helicopter antenna pods, and in-flight trailing cables, as well as 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. There have also been tests of Olympic ski gear, space suits for tare evaluations related to underwater simulations of weightless space activity, racing bicycles, subway station entrances, and Olympic rowing shells for oarlock system drag comparisons.

In its more than 75 years of operation, Wright Brothers Wind Tunnel work has been recorded in hundreds of theses and more than 1,000 technical reports.

The WBWT faculty and staff include Mark Drela and technical instructor David Robertson.

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 order 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 of engineering.

The department offers an aerospace engineering degree (Course 16: Aerospace Engineering). The degree emphasizes aerospace fundamentals and allows students to explore various aspects of aerospace engineering in greater depth through a wide selection of professional area subjects. In addition, an 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 more flexible program, Course 16-ENG, with an emphasis on aerospace-related engineering. Given that the practice of aerospace engineering has become increasingly multidisciplinary, the 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. The 16-ENG degree program offers concentrations in aerospace software engineering, autonomous systems, embedded systems and networks, computational engineering, computational sustainability, energy, engineering management, environment, space exploration, and transportation.

The skills and attributes emphasized in all of our 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, the disciplinary content, and 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. In particular, the department participates in the Institute's new computational science and engineering doctoral degree, administered by the Center for Computational Engineering (CSE). Students enrolled in the AeroAstro CSE program can specialize in a computation-related aerospace field through focused coursework and a doctoral thesis.

Graduate Enrollment

	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15–16
Total graduate student body	236	226	226	229	246	241	233	228
SM**	148	130	111	121	125	117	107	111
PhD***	88	96	115	108	121	124	126	117
Minority								
SM	8	9	7	9	12	13	17	18
PhD	6	4	6	5	6	5	5	4
Female								
SM	32	30	22	21	23	23	26	25
PhD	23	17	20	16	22	26	25	22

*Numbers based on fifth-week enrollment data.
**Includes students pursuing only a 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

	06–07	07–08	08–09	09–10	10–11	11–12	12–13	13–14	14–15	15-16
Sophomores	65	57	74	57	51	45	66	71	56	47
Juniors	60	66	55	65	47	46	43	53	65	54
Seniors	56	66	62	58	68	47	45	44	56	65
Total	**181**	**189**	**191**	**180**	**166**	**138**	**154**	**168**	**177**	**166**
% women	31	30	30	34	29	31	37	36	36	35
% underrepresented minorities	19	14	32	40	28	38	30	31.5	32	34

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