# Department of Aeronautics and Astronautics

The MIT Department of Aeronautics and Astronautics (AeroAstro) is a vibrant community of 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 in the nation 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 fluctuates slightly from year to year and is currently at approximately 150. Our graduate programs, offering SM, PhD, and ScD degrees, serve approximately 225 candidates annually. Both the department's undergraduate and graduate programs are among the most competitive in the country.

At the end of AY2017, the department's faculty count stood at 35.5 (including seven core and three affiliate faculty from the MIT Institute for Data, Systems, and Society), including 1.5 full-time-equivalent [FTE] faculty members on professional leave (Olivier de Weck at Airbus and David Mindell, who is writing a new book) and two on institutional leave (Ian Waitz and Dan Hastings). Of note, department faculty member Ian Waitz resigned his position as dean of the School of Engineering effective June 30, 2017, moving into the newly created vice chancellor role at the Institute.

A highly anticipated event was a May 10, 2017, downlink question-and-answer session with Course 16 alumnus Jack Fischer aboard the International Space Station (ISS). Students were invited to pose questions in real time with astronaut Fischer. Retired astronaut Mike Collins (Gemini 10, Apollo 11), who was visiting the campus for an AeroAstro presentation, attended and surprised Fischer with a question of his own.

*AeroAstro students queue up for a chance to ask questions of astronaut and Course 16 alumnus Jack Fischer aboard the International Space Station.*

Department researchers and students played a leading role in the September 2016 launch of OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security Regolith Explorer) by the National Aeronautics and Space Administration (NASA); this spacecraft is scheduled to rendezvous with the Bennu asteroid in 2.5 years, collect a piece of the asteroid, and return it to Earth. REXIS (REgolith X-ray Imaging Spectrometer), an X-ray spectrometer designed and built by MIT students that is aboard OSIRIS-REx, will reveal Bennu's composition and map its surface. Also, two asteroids formerly known as 120351 and 134178 have been renamed, respectively, "Beckymasterson" and "Markchodas," honoring the role of their namesakes (research engineer Becky Masterson and graduate student Mark Chodas) in the asteroid study and sample return mission.

AeroAstro graduate student Max Opgenoord and the MIT Hyperloop Team competed in the final round of the SpaceX Hyperloop Competition in January 2017, distinguishing themselves by being the first of only three teams to do a run in a low-pressure tube, successfully demonstrating stable magnetic levitation. The team earned third place in the Design and Construction category and was presented the Safety and Reliability Award.

Like many at MIT, the Department of Aeronautics and Astronautics has been affected by policies promulgated by the new administration in Washington, DC. Seizing this opportunity to express its support for diversity and inclusion, the department offered the following statement on the administration's immigration order:

> The MIT Department of Aeronautics and Astronautics adds its concern to those expressed by many others regarding the executive order that indiscriminately bans individuals of selected countries from entering the United States. For more than 100 years our department has welcomed faculty, researchers, students, and staff from around the world. Many have adopted the United States as their home, enriching American lives through landmark aerospace research, innovation, and entrepreneurship; while offering devotion to our democracy and freedoms.
>
> The AeroAstro community welcomes all people who make America strong through diversity, inclusion, and intellect, no matter where they come from. We fervently oppose any efforts to exclude those pursuing safety, humanity, and a society to which they will contribute and in which they will flourish. We encourage you to stand with the Institute and with those in need of our friendship and help.

## Promoting Faculty Excellence

AeroAstro faculty include Hamsa Balakrishnan, Steven Barrett, Kerri Cahoy, Edward Crawley, David Darmofal, Olivier de Weck, Mark Drela, 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, David Mindell (0.5 FTE, dual appointment with the Program in Science, Technology, and Society), Eytan Modiano, Dava Newman (on leave while serving as NASA deputy administrator through January 2017), 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; see above), 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. Hired after a rigorous search in AY2016, Carmen

Guerra-Garcia remains in the employ of Boeing in Madrid; she will join the AeroAstro faculty in January 2018. With new faculty search committee chair Steven Barrett at the helm in AY2017, the department hired Luca Carlone, slated to join AeroAstro in late 2017.


*Professor Warren Hoburg is one of 12 new NASA astronaut trainees, selected from 30,000 applicants.*

NASA selected junior faculty member Warren Hoburg as a member of its 2017 astronaut candidate class. Professor Hoburg has tendered his resignation, relocating to Houston for training.

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. Also, Dean Waitz has taken the opportunity to visit the department each semester with updates.

Leadership continues to hold regular meetings with junior faculty. 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

- Paulo Lozano was promoted to full professor.
- Nick Roy was promoted to full professor.

## Recognition

- Professor Nick Roy and postdoc Rohan Paul received the Best Paper Award at the Robotics: Science and Systems conference for "Efficient Grounding of Abstract Spatial Concepts for Natural Language Interaction with Robot Manipulators."
- Professor Hamsa Balakrishnan, graduate student Karthik Gopalakrishnan, and Richard Jordan of Lincoln Laboratory won the Best Paper (System Performance) Award at the International Conference on Research in Air Transportation for "Architecting Delay Dynamics: An Air Traffic Network Example."
- Professor Ed Crawley has been elected a member of the Engineering Sciences Section of the International Academy of Astronautics.
- Professor Dava Newman received the Taylor Award from the Aerospace Human Factors Society; this award, the society's most prestigious, recognizes outstanding contributions in the field of aerospace human factors.
- The National Academy of Engineering selected Professor Leia Stirling to participate in its 2016 U.S. Frontiers of Engineering program.
- Professor Paulo Lozano received a Technical Excellence Award from the American Institute of Aeronautics and Astronautics (AIAA) for his CubeSat ion electrospray propulsion system.
- Professor Sertac Karaman won the IEEE (Institute of Electrical and Electronics Engineers) Robotics and Automation Society Early Career Award.
- Professor Edward Greitzer has been selected to receive the 2017 AIAA Reed Aeronautics Award, "the highest honor an individual can receive for notable achievement in aeronautics."
- Professor Emeritus Alan Epstein has been named a 2017 AIAA Honorary Fellow.
- Professor Daniel Hastings has been elected a member of the National Academy of Engineering.
- Professor Oli de Weck won an MIT Office of Digital Learning Teaching with Digital Technology Award for his work in engineering management courses; he was nominated for the award by his students.
- Professor Sheila Widnall was presented a Freshman Faculty Adviser Award.
- Professor Emeritus Alan Epstein received the 2017 R. Tom Sawyer Award from the American Society of Mechanical Engineers.
- The Society of Photo-Optical Instrumentation Engineers chose Professor Richard Binzel and the Pluto New Horizons team as recipients of the 2017 George W. Goddard Award.

- Professor David Darmofal 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 Warren Hoburg 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."
- Peter Belobaba was awarded the 2016 Impact Prize by the Institute for Operations Research and the Management Sciences (INFORMS) at its annual meeting in October.

## Promoting Excellence in Graduate Education

AeroAstro received 662 applications for admission to its graduate programs, admitting 96 applicants (an admission rate of 14%). Of the 96 students admitted, 72 enrolled, for a yield of 75%. Women accounted for 24% of the entering class, while 10% of the class met the criteria for underrepresented minority groups.

*U.S. News & World Report* ranked the department's graduate program second in the nation along with Georgia Tech. During the period September 2016 through June 2017, the department graduated 24 PhDs and 63 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

- Graduate student Todd Sheerin has been awarded a National Defense Science and Engineering Graduate Fellowship. These highly competitive fellowships, awarded to US citizens and nationals who intend to pursue a doctoral degree in one of 15 supported disciplines, are three years in duration, pay for full tuition and all mandatory fees, and include a monthly stipend and up to $1,000 a year in medical insurance.
- Graduate student Max Opgenoord has been included in *Improper Bostonian* magazine's list of "the city's next generation all-stars."
- The National Space Grant Foundation announced that graduate student Angie Crews has been named a John Mather Nobel Scholar.
- Graduate student Cory Frontin has been awarded a NASA Graduate Aeronautic Scholars Fellowship.
- *MIT Technology Review*'s Spanish edition named PhD candidate Fernando Mier-Hicks one of its 10 Young Innovators Under 35.

- PhD candidate Mike Wittman won the INFORMS Aviation Applications Section Best Student Presentation Award at the organization's annual meeting.
- AeroAstro graduate student Martin York was named the 2016 Air Force Cadet of the Year.
- *Aviation Week* included AeroAstro graduate student Alex Feldstein on its 2017 "Tomorrow's Engineering Leaders: The 20 Twenties" list.
- Zonta International, an organization that works to advance the status of women, awarded its 2017 Amelia Earhart Fellowships to AeroAstro students Tam Nguyen, Anne Collin, and Catherine Miller.
- Tony Tao received the $15,000 Lemelson-MIT "Drive it!" award for his development of a small, mid-air-deployable, folding electric drone and adaptable aircraft manufacturing architecture.
- The Rene H. Miller Prize for Excellence in Systems Engineering, which is awarded to the student (undergraduate or graduate) who has done the best piece of work in systems engineering in the department, was presented to Michael Burton for sustained excellence in applying geometric programming techniques to the conceptual and preliminary design of a long-endurance unmanned aerial vehicle (UAV) and for leadership in the manufacturing of the wing subassembly.
- Arthur Chen-wei Huang won the 2017 AIAA Teaching Assistantship Award, given to a teaching assistant in a Course 16 subject for outstanding commitment to pedagogy, inspiration, and superior contributions.
- The AeroAstro Graduate Teaching Assistantship Award was presented to Cody Karcher, Jacqueline Thomas, and Tony Tao for their tireless commitment to the students of 16.821 Flight Vehicle Development and for their contributions to the development and flight test of the Jungle Hawk Owl.

## Promoting Excellence in Undergraduate Education

Once again, the department's undergraduate program was ranked first in the nation by *U.S. News & World Report*. Never resting on its laurels, the department is always seeking ways in which to improve the quality of the program.

The department remains committed to promoting undergraduate research, hiring a number of students through the Undergraduate Research Opportunities Program (UROP). In AY2017, AeroAstro hired 219 UROP students, of whom 60 (27%) were freshmen. During summer 2017, 18 of the department's 53 UROP students (33%) were rising sophomores.

The 16.01/16.02 Unified Engineering subject, AeroAstro's sophomore-level introduction to the foundations of aerospace engineering, has been modified to better focus on four individual disciplines: materials and structures, signals and systems, thermodynamics, and fluids. These disciplines are now being taught separately, with cross-disciplinary labs and lectures providing for unification between the subjects. Moreover, the department has introduced a new design subject in robotics (16.405 Robotics: Science and Systems I) that can be used to fulfill laboratory and CI-M (Communication Intensive in the Major) requirements. This subject provides a new alternative in autonomous systems to our traditional design subjects in aircraft and spacecraft systems.

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.

## Recognition

- Apollo Program Prize, given to the AeroAstro student who conducts the best undergraduate research project on the topic of humans in space: David Sherwood for his innovative and dedicated work, both analytical and experimental, on spatial orientation under altered gravitational forces in a centrifuge at the Massachusetts Eye and Ear Infirmary, and Tiera Guinn and Emily Widder for their research on the water vapor transmission rate of a mechanical counter-pressure suit on Mars.
- Andrew J. Morsa Prize, given for demonstration of ingenuity and initiative in the application of computers to the field of aeronautics and astronautics: David Sherwood for leadership in architecting, integrating, and testing the 16.82x avionic sub-subsystem of the Jungle Hawk Owl UAV and Allan Ko for his research in experimental validation of mesh network scaling laws. The latter work will guide the development of improved theoretical mesh networking models, contributing to the greater goal of engineering feasible, large-scale wireless mesh networks.
- 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: Madeleine Jansson for her deep commitment to learning, passion for aerospace engineering, and generous spirit and Clarisa Sorrells for her persistence in the pursuit of an aerospace engineering education and for maintaining an unassuming sense of humor.
- Admiral Luis De Florez Prize, awarded for "original thinking or ingenuity": Andrew Kurtz and Eric Riehl for designing, building, and testing two transmission architectures for a hydrocarbon-fueled multirotor aerial vehicle.
- James Means Award for Excellence in Flight Vehicle Engineering: Andrew Kurtz for overall contributions to the development of the Jungle Hawk Owl and for ingenuity in integrating a fuel-injected engine and alternator for the propulsion subsystem and Robert Binkowski for excellence in developing and fabricating composite parts for the Jungle Hawk Owl.

- James Means Award for Excellence in Space Systems Engineering: the 16.83 Launch, Navigation, and Control Team—Jeremy Stroming, Emily Widder, and Tori Wuthrich—for excellence in designing mission trajectories to rendezvous with and inspect the Apophis asteroid.
- 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: Zachary Bierstedt, Nicholas “Nikko” James, and Tori Wuthrich.
- Rene H. Miller Prize for Excellence in Systems Engineering, awarded to a student (undergraduate or graduate) who has done the best piece of work in systems engineering in the department: Andrew Adams for excellence in leadership and for organizing the systems engineering effort in the design of a mission to investigate the Apophis asteroid.
- David Shapiro Memorial Award, given to AeroAstro undergraduate students to pursue special aeronautical projects and/or to support foreign travel for the enhancement of scientific/technical studies and research opportunities: the department-sponsored MIT Rocket Team (to compete in the Spaceport America Cup in Las Cruces, NM, in June 2017) and Rachel Morgan (to attend the AIAA USU (Utah State University) Conference on Small Satellites in Logan, UT, in August 2017). Also, the MIT Rocket Team earned second place in the 10,000-foot commercial-off-the-shelf propulsion category in the Spaceport America Cup with its Project Raziel.

## Improving AeroAstro’s Physical Space

The department continues to make great strides in improving our physical space. The long-awaited first and most dramatic phase of renovations to Building 31 is nearly complete. Financed by AeroAstro, the Department of Mechanical Engineering, the School of Engineering, the Institute, and generous benefactors, the renovations are extensive, bringing the building into the 21st century. Housing the Kresa Center for Autonomous Systems, Northrop Grumman Foundation Flight Deck, Gorenberg-Stickney Conference Room, and Kaminski Laboratories, Building 31 will prove a valuable resource.

*Building 31, home of the Gas Turbine Laboratory and autonomous systems research, has undergone a $52 million renovation.*

The finished project will include a newly constructed 3,200-squarefoot high-bay space with 24-foot-tall ceilings, a motion capture system to test unmanned autonomous flying vehicles, and a seamless projection system allowing for novel approaches to working with autonomous vehicles. In addition to the high-bay space, we have created two newly renovated lab spaces that feature motion capture systems.

Building 31 is now connected to Building 37 via a third-floor bridge, allowing for greater collaboration between our researchers. The building project has provided eight newly renovated faculty offices, upgraded systems for the Gas Turbine Laboratory, and a 4,800-square-foot outdoor deck that will enable outdoor vehicle flying tests and provide social space.

The second phase of construction, which will be complete by March 2018, will create approximately 5,000 square feet of joint flexible maker space between AeroAstro and Lincoln Laboratory to house Beaver Works 2.0. This space will be dedicated to tools needed for student research and capstone projects.

While the renovation of Building 31 has improved the conditions of the Gas Turbine Laboratory and created 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 wind tunnel is often down for repairs, interfering with not only research but also education. While we have completed a study of Building 17 (the wind tunnel laboratory) and have plans to take this on as our next large capital project, locating funding will require that we redouble our development efforts. Our plans are to connect the tunnel and Building 17 to Building 33 via two avenues: one into the hangar and the other directly into the Arthur and Linda Gelb Laboratory, allowing students direct access to the test section.

With the tunnel priced out at $17 million, it may benefit from a $10 million gift from a long-time corporate ally and partner. We are developing the prospect pipeline for the remaining $7 million of the project and will be approaching alumni, friends, and industry partners over the next two years.

Minor renovations have recently taken place in Building 33, allowing for improved access to the department as well as to the newly renovated 35-225 classroom. The department advocated for both upgrades and is pleased that the classroom is now among the best at the Institute, with modern audiovisual systems, an improved layout, and modern furniture. With Building 31 nearing completion, we can now continue to make improvements in the care and maintenance of existing space. Fundraising to support space and facilities renovation remains a top priority.

Quantity and quality of space remains a constant challenge for the department, although we have continued to make improvements in the care and maintenance of existing space.

## Resource Development

As the department prepares for the reopening of the Sloan Laboratories for Aircraft and Automotive Engines (Building 31) in September 2017, we recognize MIT alumni and friends who made the renewal possible, including Kent Kresa, Art Samberg, Mark Gorenberg, Paul Kaminski, Dan Schwinn, Northrop Grumman, and the hundreds of others who have supported our development fund over the years. Other significant gifts to the department in 2016–2017 came from alumnus George Elbaum in support of graduate fellowships, Autel Robotics in support of autonomous systems research, and Claudia Alemán in support of an endowed chair honoring her father, Miguel Alemán, who sits on our visiting committee.

## Other Activities

In January 2017, the department once again took 40 sophomore students on an educational trip to the West Coast. Without doubt, each successive year's trip is better than the previous one. In 2017, the group made visits to Amazon Prime Air, Boeing (Everett factory and the flight line), Blue Origin, JPL, SpaceX, Northrop Grumman Aerospace Systems, and Scaled Composites. 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. It was a phenomenal experience for all involved, and the trip will continue in future years. We are investigating the possibility of philanthropic support for this annual event.


*A much-anticipated Independent Activities Period event is the department's annual trip to the West Coast to visit aerospace manufacturers.*

The University of Colorado joined MIT and Stanford in presenting the 2017 Women in Aerospace Symposium, hosting the event in Boulder for the first time. MIT faculty members Leia Stirling and Jaime Peraire traveled to Boulder to represent the department, taking part in panels focusing on academic job searches and academic careers, respectively. Department graduate students Mayara Conde Rocha Murca and Sherrie Hall presented on their research. The 2018 event is slated for Stanford.

## School Awards

Bill Litant 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.

## Departmental Awards

Kathryn Fischer received the Wings Award, which recognizes an individual support staff member in AeroAstro for excellence.

Dave Robertson 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 graduate students Charlotte Lowey and Alex Feldstein.

## 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. More recent data are pending.

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 methods for design, optimization, control, and decision making in aerospace and other complex systems. ACDL research addresses a comprehensive range of topics including computational fluid dynamics and mechanics; numerical analysis; uncertainty quantification; statistical inference and data assimilation; surrogate, reduced-order, and multi-fidelity modeling; high-performance computing; and simulation-based design.

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, high-order methods, multi-level 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. Efforts in statistical inference and data assimilation are aimed at fusing physics-based models with observational data and using data to guide the construction and calibration of models. Current research has developed effective algorithms for the solution of large-scale statistical inverse problems, for high-dimensional Bayesian filtering, for uncertainty propagation and solution of stochastic partial differential equations (PDEs), and for optimal experimental design. These algorithmic developments are supported by ongoing work in error estimation, solution adaptivity, and local or global sensitivity analysis. Applications range from aerospace vehicle design to large-scale geophysical and environmental problems.

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 Professors Youssef Marzouk (director), David Darmofal, Mark Drela, Woody Hoburg, Jaime Peraire, Qiqi Wang, and Karen Willcox. The research staff includes Steven Allmaras, Marshall Galbraith, 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 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 multi-year Draper Laboratory University Research and Development Program project on precision landing of guided parafoils, with robustness to large and dynamic wind environments. Finally, ACL is participating in a multi-year, multi-university research initiative focused on enabling decentralized planning algorithms under uncertainty. Ongoing ACL research has demonstrated that the use of flexible nonparametric Bayesian models for learning models of uncertain environment can greatly improve planning performance.

*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 Professors Jonathan How and Steven Hall.

### Autonomous Systems Laboratory

The Autonomous Systems Laboratory (ASL) is a virtual lab led by Professors Brian Williams and Nicholas Roy. Williams's group, the Model-based Embedded and Robotic Systems 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.

- 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.

- Human-robot interaction between an astronaut and the ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) 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 robot, a six-legged/wheeled lunar rover that performs heavy lifting and manipulation tasks by using its legs as arms.

## Communications and Networking Research Group

The primary goal of the Communications and Networking Research Group (CNRG) 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.

During the past 10 years, CNRG developed a number of network control algorithms for wireless networks. However, these schemes were developed assuming that they can be applied universally, to all nodes in the network. In recent years, the group has been focusing on the design of network control algorithms that can operate efficiently using legacy network devices. Their approach uses a novel overlay architecture for implementing optimal network control algorithms over a legacy network with a limited number of overlay nodes. This new paradigm allows optimal control algorithms to be incrementally deployed alongside existing schemes, thus providing a migration path for new control algorithms and the promise of dramatic improvements in network performance. In a related area, Professor Modiano and graduate student Abhishek Sinha developed a new framework for throughput-optimal data dissemination in wireless networks in the presence of an arbitrary mix of unicast, broadcast, multicast, and anycast traffic. In particular, they developed an online dynamic policy, universal max-weight (UMW), that optimally routes packets and schedules transmissions. UMW is the first throughput-optimal algorithm in the context of generalized network flow problems.

The group continues to work on the robustness of interdependent networks. Many engineering systems involve interactions between two or more networked systems. Cyber-physical systems, for example, consist of networked computer systems that are used to control physical systems such as the power grid, water or gas distribution systems, and transportation networks. While this cyber-physical interaction is critical for the functionality of the overall system, it also introduces vulnerabilities in the form of interdependence failure cascades, wherein failures in the cyber network lead to failures in the physical network, and vice versa. Over the past year, Professor Modiano and his student Jianan Zhang have developed a novel model for interdependence networks and new methods for assessing reliability in such networks. Their novel approach will lead to new understandings of interdependence between networked systems such as the power grid and the communication networks used to control the grid.

In recent years, the group has been pursuing industrial collaborations in order to increase the impact of their work on practical systems. To that end, the group is involved in a joint project with BBN Technologies on resilient overlay networks, a project with Qualcomm on mission-critical communications, and a close collaboration with researchers at Lincoln Laboratory on the design of network architectures and protocols for military communications. CNRG's research crosses disciplinary boundaries by combining techniques from network optimization, queuing 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 (GTL) is to advance the state of the art in fluid machinery for power and propulsion. GTL's research is focused on advanced propulsion and energy systems and turbomachinery. Activities include computational, theoretical, and experimental research in the following areas:

- Loss mechanisms and unsteady flows in fluid machinery
- Dynamic behavior and stability of compression systems
- Instrumentation and diagnostics
- Advanced centrifugal compressors and pumps for turbocharging and energy conversion
- Gas turbine engine and fluid machinery noise reduction
- Novel aircraft and hybrid-electric propulsion system concepts for reduced environmental impact
- Multiphase and non-ideal fluid machinery design, such as cavitating rocket engine inducers and supercritical carbon dioxide compressors

The laboratory maintains strong ties with industry and government research in the area of propulsion and turbomachinery technology, as well as with other academic institutions that are leaders in this field. For example, GTL is involved in collaborative projects with major American aeroengine manufacturers and European and Japanese companies, and thus there are many connections between work in GTL and "real-world" problems. Research support also comes from NASA centers. In addition to inhouse experimental work, research is sometimes carried out at government or industry facilities. One example is recent research sponsored under the NASA N+3 program and in collaboration with Aurora Flight Sciences and Pratt & Whitney; in this work, GTL developed an advanced commercial aircraft configuration with a boundary-layer-ingesting, embedded propulsion system dubbed the double bubble D8 concept.

GTL faculty and research staff include Professors David Darmofal, Fredric Ehrich, Alan Epstein (emeritus), Edward Greitzer, and Zoltan Spakovszky (director); senior lecturer Jayant Sabnis; research engineer David Hall; and senior research engineer Choon Tan.

## 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 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 Professors R. John Hansman (director), Cynthia Barnhart, and Amedeo Odoni (emeritus) and principal research scientist Peter Belobaba.

### Laboratory for Aviation and the Environment

A defining challenge for the aviation industry is to address aviation's environmental impact. The research of the Laboratory for Aviation and the Environment (LAE) seeks to support this mission by improving our understanding of aviation's impact on air quality and climate, supporting the implementation of aviation policies aimed at mitigating environmental effects, and developing and analyzing technologies to reduce aviation emissions. Specifically, LAE researchers are developing and assessing operational, regulatory, and technological mitigation options and disseminating knowledge and tools to help quantify the costs and benefits of aviation in general and mitigation approaches in particular. With the resulting know-how and tools, LAE also contributes to cognate areas of study such as transportation, energy, and the environment.

For more than two decades, LAE and its predecessors at MIT have developed tools that help in understanding and analyzing aviation's air quality, climate, and noise impact. These tools are used by researchers worldwide. The tools currently maintained at LAE include a reduced-order climate model for analyzing the historical, current, and future climate impact of aviation; forward and backward global atmospheric models to study aviation's air quality impact; and life-cycle and techno-economic models for quantifying the environmental and economic impact of alternative aviation fuels. LAE researchers apply these tools to inform domestic and international policymakers and regulators (e.g., the Federal Aviation Administration [FAA] and the International Civil Aviation Organization) about the costs and benefits of aviation policies. Thus, research at LAE directly contributes to defining global and domestic aviation policies.

A current focus in tool development at LAE is on creating a model for understanding contrails' climate impact. Contrails are the white line-shaped clouds that form behind aircraft and are considered to potentially be the most significant driver of aviation-induced global warming. To analyze contrails and their radiative forcing impact, LAE researchers are developing the Contrail Evolution and Radiation Model, a physically realistic 3D model of dynamical and microphysical processes from the jet phase at contrail formation to the diffusion phase as contrail cirrus.

LAE research also identifies technology that might enable significant reductions in aviation's environmental footprint. For example, LAE researchers are studying the environmental sustainability and economics of alternative aviation fuels. Further work assesses jet engine emission control technology and studies concepts for all-electric aircraft. In addition, LAE researchers developed a novel electric aircraft propulsion system without moving parts that was prototyped and flown for the first time in the past year.

LAE researchers apply their know-how to analyze a wide range of environmental issues beyond the aviation sector. Recent LAE studies have quantified the health impact related to the excess emissions of Volkswagen diesel cars in Germany and the United States. Other projects are examining transboundary air pollution effects in the United States and Singapore.

LAE faculty and staff include Professor Steven Barrett, director; Ray Speth, associate director; Florian Allroggen, laboratory executive officer; Jayant Sabnis; Professors Hamsa Balakrishnan, John Hansman, Ian Waitz, and Karen Willcox; and postdoctoral associate Mark Staples.

### 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 Professors 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 three main areas: the Robert C. Seamans Jr. Laboratory, the Arthur and Linda Gelb Laboratory, and the Gerhard Neumann Hangar.

#### *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 engage in 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. 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.

## 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.

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 creation of a g-loading suit to maintain muscle and bone strength, 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 Natick Soldier Research, Development, and Engineering Center; FAA; the Federal Railroad Administration; Draper Laboratory; the Center for Integration of Medicine and Innovative Technology; the Deshpande Center for Technological Innovation; and the MIT Portugal Program. The laboratory also collaborates with the Volpe Transportation Research Center, Draper, Aurora Flight Sciences, Massachusetts General Hospital, and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

MVL faculty include Professors Jeffrey Hoffman and Leia Stirling, co-directors; Professor Dava Newman; Professor Emeritus Laurence Young; Chuck Oman; and Professor Julie Shah. 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 (e.g., novel catalysts for carbon nanostructure synthesis) to structural applications of both hybrid and traditional composite 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 higher-performance advanced composites using nanotechnology. Beyond the NECST Consortium members, necstlab research is supported directly by 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.

Examples of current and past research projects include:

- Efficient de-icing of aircraft wings with integrated carbon nanotube–based heaters
- Out-of-autoclave curing of composites with aligned carbon nanotube heating
- Biofunctionalized nanoelectromechanical systems (bioNEMS) materials design and implementation in microfluidics
- Buckling mechanics
- Carbon nanostructure synthesis from nontraditional catalysts at low temperatures
- 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 Professor Brian L. Wardle (director), Professor John Dugundji (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 faraway places. Areas of research include plasma engines and plumes and their interaction with spacecraft and thruster materials, along with 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 (e.g., 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 monenergistic 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 Professors Paulo Lozano (director) and Manuel Martinez-Sanchez (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 International Space Station 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 aboard the ISS 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 more than 100 US and 50 European teams annually. The finals of the competition are run aboard the ISS by Russian cosmonauts and US and/or European Space Agency astronauts.

There have been more exciting hardware augmentations to SPHERES. Through the Visual Estimation for Relative Tracking and Inspection of Generic Objects (VERTIGO) program, a cadre of Universal Docking Ports and Halos "expansion ports" are now aboard the ISS and awaiting operations. 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.

SSL has designed, built, tested, and delivered the REXIS student collaboration instrument to OSIRIS-REx, NASA's next New Frontiers mission. OSIRIS-REx is an asteroid sample return mission scheduled to visit the near-Earth asteroid Bennu. REXIS, one of five instruments onboard, will use a 2 × 2 array of Lincoln Laboratory–designed charged-coupled devices to measure the X-ray fluorescence from Bennu, allowing characterization of the surface of the asteroid 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 the Department of Earth, Atmospheric and Planetary Sciences (EAPS) and AeroAstro, and Rebecca Masterson are leading the project in collaboration with EAPS, the Kavli Institute for Astrophysics and Space Research, and the Harvard College Observatory. Over the course of the project, REXIS has included the work of more than 50 undergraduate and graduate students. The instrument was successfully integrated into the OSIRIS-REx spacecraft in December 2015. The REXIS student team supported assembly, test, and launch operations at Lockheed Martin and is wrapping up testing at the Kennedy Space Flight Center.

SSL is directed by Professor David W. Miller. Professors 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 fiscal officers Suxin Hu and Ngan Kim Le and administrative assistant Marilyn E. Good. Collaborators include Professors Manuel Martinez-Sanchez (emeritus) and Paulo Lozano of AeroAstro and Professor Sara Seager of EAPS.

## Space Telecommunications, Radiation, and Astronomy Laboratory

The Space Telecommunications, Radiation, and Astronomy Laboratory (STAR Lab) is part of the Space Systems Laboratory. We focus on developing instruments and platforms that enable weather sensing on Earth and other planets, including exoplanets, and monitoring "space weather"—the highly energetic flow of radiation, or charged particles, constantly streaming toward Earth from the sun. These efforts include development of several shoebox-sized and backpack-sized satellites, called CubeSats, for weather sensing and technology demonstration work, particularly in laser communications, as well as work on much larger Hubble-sized space telescopes for direct imaging of exoplanets.

### *Weather Sensing CubeSat Projects*

*Microsized Microwave Atmospheric Satellite (MicroMAS):* MicroMAS-1 was MIT's first student shoebox-sized 3U CubeSat; this project was a collaboration with William Blackwell at Lincoln Laboratory. MicroMAS-1 launched in July 2014 and was deployed from the International Space Station in March 2015. MicroMAS is unique in that it has the ability to completely rotate its temperature-mapping payload to scan Earth and space for calibration. While a communications failure after only a few days of operation prevented us from testing the microwave radiometer payload, we obtained useful engineering data on many of our subsystems. Together with Lincoln Laboratory, we have built two MicroMAS-2 CubeSats for reflight in 2017.

*Microwave Radiometer Technology Acceleration Mission (MiRaTA):* MiRaTA, sponsored by NASA's Earth Science Technology Office, is a joint effort involving Lincoln Laboratory, The Aerospace Corporation, the University of Massachusetts Amherst, and the Space Dynamics Laboratory. This 3U CubeSat has a temperature-mapping tri-band microwave radiometer as well as a GPS (Global Positioning System) radio occultation payload that makes temperature and pressure profile measurements. MiRaTA is scheduled to launch in September 2017 from a Delta II rocket originating at the Vandenberg Air Force Base.

*TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats):* Recently selected by NASA's Earth Venture Instrument program, we will be part of the Lincoln Laboratory–led TROPICS team, building eight MicroMAS-like CubeSats with microwave radiometer payloads and supporting data calibration and analysis.

### *Technology Demonstration CubeSat Projects*

*Nanosatellite Optical Downlink Experiment (NODE):* We are working with a commercial partner that builds and flies 3U CubeSats to include our laser communications system for demonstration. NODE makes use of a MEMS fast steering mirror to achieve precise pointing for laser communications, increasing data rates and improving efficiency and security without the regulatory overhead of high-bandwidth radio systems.

*Deformable Mirror Demonstration Mission (DeMi):* DeMi will fly a MEMS deformable mirror and compact wavefront sensor on a 6U CubeSat in low Earth orbit to characterize the mirror's performance. MEMS deformable mirrors can play key roles in wavefront control systems on larger space telescopes by enabling high-contrast exoplanet imaging. DeMi is sponsored by the Defense Advanced Research Projects Agency and managed by Aurora Flight Sciences. MIT is building the optical payload and working with Blue Canyon Technologies (Boulder, CO), which is building the bus.

*Free-space Lasercom and Radiation Experiment (FLARE):* FLARE is part of the Air Force Research Laboratory's University Nanosatellite Program 9. It will fly two 3U CubeSats containing a laser communications transmitter and receiver as well as an energetic particle spectrometer.

### *Bigger Space Telescopes for Exoplanet Science*

Professor Cahoy and graduate students in the STAR Lab are supporting larger space telescopes for exoplanet science, including MIT's Transiting Exoplanet Survey Satellite (TESS), led by George Ricker. We are part of the science investigation team for the Wide Field Infrared Survey Telescope mission, which will include a wavefront control system and an internal coronagraph on a Hubble-sized space telescope. We also support exoplanet mission science and technology definition teams such as Exo-C and HabEx.

The STAR Lab is directed by Professor Kerri Cahoy.

## Strategic Engineering Research Group

Strategic engineering is the process of architecting and designing complex systems and products in a way that deliberately accounts for future uncertainty in order to maximize life-cycle value. The Strategic Engineering Research Group (SERG) focuses on research in systems engineering and technology management for systems with lifetimes of decades or, in some cases, centuries.

In the area of human space exploration and settlement, we are a leading laboratory in systems analysis and campaign planning. Our SpaceNet 2.5r software is available under a GNU open license and performs detailed network and trajectory analysis, propulsion and logistics calculations, and feasibility checks for proposed campaigns. HabNet is a new space habitation modeling and simulation environment that quantifies the flow of resources such as water, gases, propellants, and foods through closed- or semiclosed-habitat systems. Our projects in AY2017 expanded the efforts of the group into the area of in-space manufacturing with a grant from the NASA Office of Emerging Space. In this work, we showed that the production of solar arrays in space can start paying off with a cumulative production volume of as little as 310 kW at a cost of approximately $438 per watt. Also, together with the MIT Department of Architecture, we contributed to the winning submission at the 2017 NASA RASC-AL (Revolutionary Aerospace Systems Concepts–Academic Linkages) graduate competition on the topic of an evolvable space hotel.

A newer direction for SERG is the study of distributed satellite missions for Earth science with network-based systems under uncertainty, as well as the modular design of platform-based systems for future aerospace and defense applications. As part of the Goddard Space Flight Center's Tradespace Analysis Tool for Constellations project, we contribute to a capability for architecting future distributed Earth science missions. Integrated analysis of multi-spectral satellite imagery for systems modeling of terrestrial infrastructure is one of SERG's current areas of interest.

Awards and recognition received by SERG members in 2016–2017 included a Best Paper Award at the 26th INCOSE (International Council on Systems Engineering) International Symposium and the MIT Teaching with Digital Technology Award. The group's current funding sources include NASA, Draper Laboratory, the US Navy, and King Abdulaziz City for Science and Technology.

SERG is directed by Professor Olivier de Weck, who is currently on leave from MIT as senior vice president for technology planning and roadmapping at Airbus. The group's associate directors are Afreen Siddiqi, Bryan Moser, and Eric Rebentisch.

### System Architecture Laboratory

Every built system has an architecture. Products such as communications satellites, automobiles, semi-conductor capital equipment, and commercial aircraft are defined by a few key decisions made early in each program's life cycle. The emerging field of system architecture aims to understand what patterns emerge across disparate domains; that is, "what makes good architecture?"

In the System Architecture Laboratory, we study the early-stage technical decisions that will determine system performance. We have helped architect systems ranging from lunar surface exploration vehicles to oil exploration platforms for ice-bound drilling. Past research partners and sponsors include Sikorsky, NASA, Pratt & Whitney, Boeing, BP, Caterpillar, AMGEN, Verizon, and Amazon.

Our key contention is that by identifying the most important initial technical decisions and exhaustively enumerating options, we can identify the best potential designs before detailed design activities begin. Our work stands in contrast to a traditional trade-study perspective in which two to four designs are compared without reference to the intervening options or to a fully explored trade space.

The lab's efforts are divided into five research areas:

- System architecture methods and computational tools
- Space communications
- Architecting space exploration
- Stakeholder analysis methods and tools
- Commonality and platforming

Our book System Architecture: Strategy and Product Development for Complex Systems provides details on the lab's work.

The System Architecture Laboratory was founded by AeroAstro professor Edward F. Crawley. Bruce G. Cameron is the lab's director.

### 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 structures 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, FAA, and the Department of Energy.

The System Engineering Research Laboratory is directed by Professor 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 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.

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

### Wireless Information and Network Sciences Laboratory

The Wireless Information and Network Sciences Laboratory (WINSLab) 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, intrinsically secure networks, ultra-wideband systems, quantum information science, and space communications systems. Details of a few specific projects are given below.

The group is working on location-aware networks in GPS-challenged environments, providing highly accurate and robust positioning capabilities for military and commercial terrestrial and aerospatial networks. It has developed a foundation for the design and analysis of ubiquitous location-aware networks from the perspective of theory, algorithms, and experimentation. This includes derivation of performance bounds for network localization and navigation, the design of efficient cooperative localization algorithms, and development of realistic localization systems tested via network experimentation. The system design also relies on channel models obtained through a state-of-the-art apparatus built by the team for automated channel measurements over a range of 2–18 GHz. The apparatus is unique in that extremely wideband signal measurements, more than twice the bandwidth of conventional ultra-wideband systems, can be captured with high-precision positioning capabilities. WINSLab members are also investigating physical-layer security in large-scale wireless networks, which is expected to play increasingly important roles in new paradigms for guidance, navigation, and control of unmanned aerial vehicle networks. In addition, they have proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and interference engineering.

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 in Italy, the University of Lund in Sweden, the University of Oulu in Finland, the King Abdullah University of Science and Technology in Saudi Arabia., Kyung Hee University in Korea, the Singapore University of Technology and Design, Tsinghua University in China, Draper Laboratory, the Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Professor Moe Win directs the WINSLab.

### 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 nearly 80 years of operation, Wright Brothers Wind Tunnel work has been recorded in hundreds of theses and more than 1,000 technical reports.

Wright Brothers Wind Tunnel faculty and staff include Professor 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 programs 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.

As noted above, 16.01/16.02 Unified Engineering, the department's introduction to the foundations of aerospace engineering, has been modified to better focus on four individual disciplines (materials and structures, signals and systems, thermodynamics, and fluids). These disciplines are now being taught separately. Also as noted, the department has introduced a new design subject in robotics (16.405) that can be used to fulfill laboratory and CI-M requirements.

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. Students enrolled in the AeroAstro computational science and engineering program can specialize in a computation-related aerospace field through focused coursework and a doctoral thesis.

**Graduate Enrollment***

| Enrollment type | 2009–2010 | 2010–2011 | 2011–2012 | 2012–2013 | 2013–2014 | 2014–2015 | 2015–2016 | 2016–2017 |
|---|---|---|---|---|---|---|---|---|
| **Total graduate student body** | **226** | **226** | **229** | **246** | **241** | **233** | **228** | **223** |
| SM** | 130 | 111 | 121 | 125 | 117 | 107 | 111 | 107 |
| PhD† | 96 | 115 | 108 | 121 | 124 | 126 | 117 | 116 |
| Underrepresented minorities SM | 9 | 7 | 9 | 12 | 13 | 17 | 18 | 11 |
| Underrepresented minorities PhD | 4 | 6 | 5 | 6 | 5 | 5 | 4 | 4 |
| Women SM | 30 | 22 | 21 | 23 | 23 | 26 | 25 | 22 |
| Women PhD | 17 | 20 | 16 | 22 | 26 | 25 | 22 | 17 |

*Numbers based on fifth-week enrollment data.

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

†Students who have passed the doctoral qualifying exam.

## Undergraduate Enrollment

| Enrollment type | 2007–2008 | 2008–2009 | 2009–2010 | 2010–2011 | 2011–2012 | 2012–2013 | 2013–2014 | 2014–2015 | 2015–2016 | 2016–2017 |
|---|---|---|---|---|---|---|---|---|---|---|
| Sophomores | 57 | 74 | 57 | 51 | 45 | 66 | 71 | 56 | 47 | 50 |
| Juniors | 66 | 55 | 65 | 47 | 46 | 43 | 53 | 65 | 54 | 43 |
| Seniors | 66 | 62 | 58 | 68 | 47 | 45 | 44 | 56 | 65 | 60 |
| **Totals** | **189** | **191** | **180** | **166** | **138** | **154** | **168** | **177** | **166** | **153** |
| Women (%) | 30 | 30 | 34 | 29 | 31 | 37 | 36 | 36 | 35 | 30 |
| Underrepresented minorities (%) | 14 | 32 | 40 | 28 | 38 | 30 | 31.5 | 32 | 34 | 15 |

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