Department of Aeronautics and Astronautics

Tracing its roots to 1914 when MIT first offered the class Aeronautics, the Department of Aeronautics and Astronautics (AeroAstro) is among 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 focuses on aeronautics and astronautics, the faculty is also engaged in research in a multitude of overlapping, cross-disciplinary areas.

The department's undergraduate student body is currently at about 160. Our graduate programs, offering the SM, PhD, and ScD degrees, serve approximately 225 candidates annually. Our undergraduate and graduate programs are among the most competitive in the country.

At the end of AY2018, the department's faculty count stood at 35.5. Of those, 1.5 full time equivalent (FTE) were on professional leave (Professor Olivier de Weck at Airbus, and David Mindell at Humatics) and two on institutional leave (Ian Waitz, and Daniel Hastings).

In March 2018, Jaime Peraire announced he would step down from the position of department head, effective June 30, following seven years in the role. On June 20, School of Engineering dean Anantha Chandrakasan announced the appointment of Professor Daniel Hastings as the next department head. Hastings is slated to assume the position on January 1, 2019. Until that time, Professor Edward Greitzer will serve as interim head.

The past year saw two major and historical developments related to AeroAstro facilities. On September 27, 2017, Building 31 (which is 90 years old) reopened following a $52 million renovation that turned the space into a modern center for research in autonomy, turbomachinery, energy storage, and transportation. The three-year project added nearly 7,000 square feet of new space and doubled Building 31's capacity for faculty, students, and researchers. At the heart of the building is the new Kresa Center for Autonomous Systems, an 80-foot-long by 40-foot-wide space boasting 25-foot ceilings dedicated for work in all types of autonomous vehicles, including rotor and fixed-wing aircraft. The space was enabled by a gift from MIT alumnus Kent Kresa '59, SM '61, EAA '66.

In February 2018, it was announced that AeroAstro will replace the venerable 80-year-old Wright Brothers Wind Tunnel with the largest and most advanced academic wind tunnel in the United States. To facilitate construction of the new tunnel and ongoing operations, The Boeing Company made a funding pledge to become the project's lead donor. Once funding is in place, construction of the tunnel will commence.

During the course of the year, the department's Committee on Diversity, Inclusion, and Innovation continued to develop action plans to protect and nurture the mental and physical well-being of each member of the AeroAstro community, to increase the inclusion of women and people from underrepresented minority groups, and to address other such opportunities as appropriate. In November, the department announced that, with the goal of increasing diversity in the next generation of aerospace engineers, it was creating a pool of graduate fellowships designated for women and people from underrepresented minority groups. The fellowships will be available starting in AY2018.

In January, members of AeroAstro's Class of 2020 traveled to the Seattle and Los Angeles areas on the department's fourth annual Independent Activities Period trip. Having begun this tradition in 2014, each year the department takes its sophomore class of recently declared aerospace engineering majors to visit select industry and government partners. For the vast majority of the department's students, this is their first opportunity to speak with and learn from engineers working in the field. The itinerary included Amazon Prime Air, Blue Origin, The Boeing Company, Northrop Grumman Corporation, Space Exploration Technologies Corporation, The Jet Propulsion Laboratory (JPL), and The Aerospace Corporation.

New Engineering Education Transformation

In fall 2016, the School of Engineering dean chartered New Engineering Education Transformation (NEET), a new cross-departmental, project-centric effort to rethink engineering education in a fundamental way. NEET aims to educate young engineers to build the new machines that will address societal needs. Students pursue threads that are cross-departmental and likely to be in demand when the students graduate. NEET alumnus will be prepared to work as entrepreneurs, innovators, makers, and discoverers through learning and practicing the NEET ways of thinking: cognitive approaches such as creative thinking, critical thinking, and systems thinking that can help individuals learn on their own initiative and throughout their lifetime. By participating in the pilot, students will earn an SB degree from the department they are majoring in and a NEET certificate naming the thread, all within the usual four-year duration.

NEET is co-led by Professor Edward Crawley and School of Engineering associate dean Anette Hosoi. The initiative's full-time executive director is Amitava Mitra.

Launching and hosting the NEET Autonomous Machines pilot thread in fall 2017 is well aligned with two of the four strategic thrusts identified by the Department of Aeronautics and Astronautics in its 2015 Strategic Plan (Autonomous Systems and Education). This thread covers Courses 16-ENG, 2-A, and 6-2 and was oversubscribed with more than 26 sophomores. Professor Jonathan How is the faculty lead for this thread, and Associate Professor Sangbae Kim (Mechanical Engineering) and Professor Tomas Lozano-Perez (Electrical Engineering and Computer Science) complete the faculty committee. Autonomous Machines is being offered again in fall 2018, and over 40 sophomores have signed up for the second cohort.

The high-level educational goals for the Autonomous Machines thread are as follows: develop the tools necessary to design the hardware, algorithms, and embedded software that enable robots to function with a high degree of autonomy; be well versed in the state-of-the-art theory of all aspects of autonomous robotics; demonstrate the ability to implement the theory through hands-on applications; and address open-ended design and implementation challenges.

The main organizing armature of the thread is a sequence of projects inspired by the new machines. Students choose a sequence of explicitly interdepartmental projects, while fundamentals continue to be learned in departmentally offered subjects. Students are coached in personal and interpersonal skills and are challenged to develop their ability to learn by themselves.

Sophomore Year

- Fall semester: Students take a weekly, hands-on, three-unit seminar where they learn how to program an autonomous, mini smart car using sensor feedback to specify the car's behavior on an obstacle track. This seminar prepares the sophomores for their robotics competition in the spring as well as future classes in autonomous control.
- Spring semester: There's a 12-unit project class, 2.S007 Design and Manufacturing of Robotic Systems, to develop students' competence and self-confidence as design engineers through an active learning approach via a major design-and-build project that students work on as individuals.

Junior Year

- Fall semester: There's a weekly, hands-on, three-unit seminar where students learn how to program, fly, and race a real drone autonomously using computer vision.
- Spring semester: Students take a 12-unit project class, 16.405[J]/6.141[J] Robotics: Science and Systems, where students work in small groups to design and implement advanced algorithms on complex robotic platforms capable of agile autonomous navigation and real-time interaction with the physical world.

Senior Year

- Hands-on seminars and projects are under development. The 12-unit project class, 16.AARS Advanced Autonomous Robotic Systems will focus on large groups of students working on designing and building complex autonomous products, systems, or both.

Diversity, Inclusion, and Innovation

Following up on the department's February 2017 issuance of a statement on race and diversity, Jaime Peraire created the AeroAstro Committee on Diversity, Inclusion, and Innovation. The charge to the committee is as follows:

> Respect for and full engagement of all races, genders, religions, ethnicities, and sexual orientation form the foundation of our behavior and commitment to diversity and inclusion. The AeroAstro Committee on Diversity, Inclusion, and Innovation is charged with developing action plans to protect and nurture the mental and physical well-being of each member of our community, to increase the inclusion of underrepresented minorities and women, and to address other such opportunities as appropriate.

The committee is chaired by Professors Wesley Harris and Dava Newman. With the intention of soliciting maximum input, faculty are joined on the committee by members of staff, as well as representatives of the undergraduate and graduate student bodies.

During the course of the year, the committee gathered data and information regarding the status of diversity and inclusion within the department and throughout the Institute as a whole, with the goal of assessing the climate within the department and creating a strategic plan to address the committee's charge. The committee also met with individuals who have experience and expertise in both data collection and diversity issues. For AY2019, the committee anticipates completing its strategic plan and implementing steps to address issues of inclusion of women and people from underrepresented minority groups in the department's ranks.

In AY2018, the committee identified an initial goal of improving the diversity of the graduate student pool, began significant outreach efforts to attract a diverse pool of candidates, and established a number of fellowships to ensure that funding was not a barrier to diversifying the graduate student body.

Staff

Promoting Faculty Excellence

AeroAstro faculty include:

Hamsa Balakrishnan (associate professor)

Steven Barrett (associate professor)

Kerri Cahoy (associate professor)

Edward Crawley (Ford Foundation Professor of Engineering)

David Darmofal (professor)

Olivier de Weck (professor)

Mark Drela (Terry J. Kohler Professor)

Edward Greitzer (H. N. Slater Professor in Aeronautics and Astronautics)

Steven Hall (professor)

R. John Hansman (T. Wilson (1953) Professor in Aeronautics)

Wesley Harris (Charles Stark Draper Professor of Aeronautics and Astronautics)

Daniel Hastings (Cecil and Ida Green Professor in Education)

Jonathan How (Richard Cockburn Maclaurin Professor in Aeronautics and Astronautics)

Sertac Karaman (associate professor; Class of '48 Career Development Professor)

Paul Lagacé (professor)

Nancy Leveson (professor)

Paulo Lozano (M. Alemán-Velasco Professor of Aeronautics and Astronautics)

Youssef Marzouk (associate professor)

David Miller (Jerome C. Hunsaker Professor)

David Mindell (Frances and David Dibner Professor in the History of Engineering and Manufacturing)

Eytan Modiano (professor)

Dava Newman (Apollo Program Professor)

Jaime Peraire (H. N. Slater Professor in Aeronautics and Astronautics)

Raul Radovitzky (professor)

Nicholas Roy (professor)

Julie Shah (associate professor)

Zoltán Spakovszky (professor)

Leia Stirling (assistant professor)

Ian Waitz (Jerome C. Hunsaker Professor)

Qiqi Wang (associate professor)

Brian Wardle (professor)

Sheila Widnall (Institute Professor)

Karen Willcox (professor)

Brian Williams (professor)

Moe Win (professor)

Department head during AY2018 was Jaime Peraire. Associate department head was Eytan Modiano. Hired during AY2017, Research Scientist Luca Carlone joined the faculty as assistant professor on November 9, 2017. Following a year spent at The Boeing Company Madrid after her hiring in AY2016, Carmen Guerra-Garcia joined as assistant professor on January 16, 2018. With Steven Barrett as Faculty Search Committee chair in AY2018, an offer was extended to and accepted by Richard Linares, slated to join the faculty on July 1, 2018.

Karen Willcox, a full professor in the department, made known her intention to leave the Institute for a position as director of the Institute for Computational Engineering and Sciences at University of Texas at Austin. She will depart on August 1, 2018.

Department faculty 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. Ian Waitz, dean of the School of Engineering, also takes 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 support of the leadership. In turn, Peraire and Modiano are given the opportunity to assess how well junior faculty are acclimating and to determine if any problems that might otherwise go unnoticed have arisen.

Promotions

- Qiqi Wang was promoted to associate professor with tenure, effective July 1, 2018.

Accolades

- Olivier de Weck received the MIT Teaching with Digital Technology Award.
- Dava Newman received the Women in Aerospace Leadership Award; the Henry L. Taylor Founder's Award, from the Aerospace Medical Association; the Women in Aerospace Leadership Award; the College of Engineering Honor Award, from the University of Notre Dame; the American Institute of Aeronautics and Astronautics (AIAA) Jeffries Aerospace Medicine and Life Sciences Research Award; and was named an AIAA Fellow.
- Edward Crawley received The People's Republic of China Friendship Award and was inducted as a foreign member into the Russian Academy of Science.
- Warren Hoburg received *R&D Magazine*'s Innovator of the Year award.
- Jonathan P. How became an Institute of Electrical and Electronics Engineers (IEEE) Fellow.
- Mark Drela, Karen Willcox, and Max Opgenoord SM '16, PhD '18 received Best Paper at the AIAA Theoretical Fluid Mechanics Conference.
- Julie Shah, Youssef Marzouk, Qiqi Wang, and Kerri Cahoy were named AIAA Associate Fellows.
- Mark Drela received the AIAA Reed Aeronautics Award.
- Julie Shah received the 2018 Robotics and Automation Society Early Career Award.
- Karen Willcox was named a 2018 Society of Industrial Applied Mathematics Fellow.
- Laurence R. Young was awarded the 2018 de Florez Award for Flight Simulation from AIAA and the Life Sciences and Biomedical Engineering Branch Aerospace Medical Association Professional Excellence Award.
- Luca Carlone received the IEEE Transactions on Robotics King-Sun Fu Best Paper Award.
- Eytan Modiano received an MIT Committed to Caring Award in recognition of his outstanding student advising and mentorship, and together with his students Igor Kadota and Abhishek Sinha received the IEEE Infocom Best Paper Award, the 2018 ACM MobiHoc Best Paper Award, and the 2018 INFOCOM Best Paper Award for their joint paper "Optimizing Age of Information in Wireless Networks with Throughput Constraints."

Students

Promoting Excellence in Graduate Education

AeroAstro received 737 applications for admission to its graduate programs for fall 2018, admitting 112 applicants (admission rate of 15%). Of the 112 admitted, 81 students enrolled, for a yield of 72%. Of the entering class, 32% are women, and 11% are from underrepresented minority groups.

The *U.S. News & World Report* ranked the department's graduate program second in the nation, in a tie with Georgia Institute of Technology.

During the period September 2017 through June 2018, the department graduated 23 PhDs and 52 SMs.

Continuing its 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.

Accolades

- PhD candidate Steven Chen was co-author of "Socially Aware Motion Planning with Deep Reinforcement Learning," which captured the IEEE/RSJ International Conference on Intelligent Robots and Systems 2017 Best Student Paper Award.
- The paper "Statistical Modeling of Aircraft Takeoff Weight," co-authored by PhD candidate Yashovardhan Chati, won the Best Paper (Trajectory Prediction) Award at the 12th USA/Europe Air Traffic Management Seminar.
- Doctoral candidate Akshata Krishnamurthy was presented with the 2017 Luigi G. Napolitano Award at the closing ceremony of the 68th International Astronautical Congress (IAC). The award is presented annually to "a young scientist, below 30 years of age, who has significantly contributed to the advancement of aerospace science and has given a paper at the IAC on the contribution."
- Graduate student Max Opgenoord's paper "Towards a Low-Order Model for Transonic Flutter Prediction," was named the AIAA Theoretical Fluid Mechanics Conference Best Paper of the 2017 AIAA Aviation Forum.
- AeroAstro doctoral student Julian Brown was awarded the top prize at the 2017 AIAA/Utah State University Conference on Small Satellites as a co-presenter of a star-tracking algorithm that provides significantly faster, more accurate star identification at a fraction of the current cost.
- Doctoral student Philip Caplan received the Best Technical Student Paper Award at the 2017 International Meshing Roundtable Conference (the premier conference in computational meshing) for his paper "Anisotropic Geometry-Conforming D-Simplicial Meshing via Isometric Embeddings."

- AeroAstro graduate student and air force Reserve Officers' Training Corps cadet Nicholas James was presented the US Air Force Cadet of the Year Award and also earned the Society of Military Engineers Award.
- Graduate student Frederick Daso has been presented a 2018 National Defense Science and Engineering Graduate Fellowship.
- The Zonta International Foundation named AeroAstro grad students Carla Grobler, Akshata Krishnamurthy, and Jacqueline Thomas recipients of its 2018 Amelia Earhart Fellowships.

Promoting Excellence in Undergraduate Education

Once again, the department's undergraduate program was ranked number one in the nation by *U.S. News & World Report*.

The department remains committed to promoting undergraduate research, hiring students through the Undergraduate Research Opportunity Program (UROP). In AY2018, AeroAstro hired 258 UROPs, of which 60 (23%) are first-year students and 85 (33%) are women. During summer 2018, 20 of the department's 49 UROP students (41%) were rising sophomores.

Unified Engineering, the department'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 introduced 16.405[J] Robotics: Science and Systems, a new design subject in robotics, which can be used to fulfill the laboratory and communication intensive subject in the major (CI-M) requirements. This provides a new alternative in autonomous systems to our traditional design subjects in aircraft and spacecraft systems.

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

Accolades

- General James Doolittle Award—Presented for outstanding achievement in the design, construction, execution, and reporting of an undergraduate experimental research project: Andrew C. Adams '18 and Amy Ruth Vanderhout '18.
- Andrew J. Morsa Prize—Presented for demonstration of ingenuity and initiative in the application of computers to the field of aeronautics and astronautics: Thomas J. Murphy '19.

- Yvnge Raustein Award—Presented to a Unified Engineering student who best exemplifies the spirit of Yvnge Raustein and to recognize significant achievement in Unified Engineering: Humberto L. Caldelas '20.
- James Means Award—Presented for excellence in flight vehicle engineering: Christine A. Chappelle '19.
- James Means Award—Presented for excellence in space systems engineering: Clementine D. Mitchell '18 and Rachel E. Morgan '18.
- Rene H. Miller Prize in Systems Engineering—Presented to a student who has done the best piece of work in systems engineering in the Department of Aeronautics and Astronautics: Lillian M. Clark '18, Faith Huynh '18, Maya R. Nasr '18, and Isabel M. Rayas '18
- Henry Webb Salisbury Award—Presented in memory of Henry Salisbury to a graduating senior who has achieved superior academic performance in the Course 16 undergraduate program: Oliver Jia-Richards and Isabel M. Rayas
- AeroAstro Undergraduate Teaching Assistantship Award—Presented to an undergraduate student who has demonstrated conspicuous dedication and skill in helping fulfill an undergraduate subject's educational objectives: Samir Wadhwania '18.
- AeroAstro Graduate Teaching Assistantship Award—Presented to a graduate student who has demonstrated conspicuous dedication and skill in helping fulfill an undergraduate or graduate subject's educational objectives: Igor Kadota 'G.
- AIAA Undergraduate Advising Award—Presented by the AIAA Student Chapter to a faculty or staff who has demonstrated excellence in serving as an academic advisor and has made a real positive impact on a student's time in AeroAstro: David Miller
- AIAA Undergraduate Teaching Award—Presented by the AIAA Student Chapter to a faculty or staff member who has exemplified the role of a great teacher: Jonathan How
- AIAA Teaching Assistantship Award—Presented by the AIAA Student Chapter to a teaching assistant in a Course 16 subject for outstanding commitment to pedagogy, inspiration, and superior contributions: Inderraj Singh Grewal 'G.

Resource Development

Alumni and friends of the department continue to be generous with their support of AeroAstro.

In September 2017, the department celebrated the completion of the newly restored and refurbished Building 31. Donors to whom the department owes a debt of gratitude include Kent Kresa, the Miguel Alemán family, Mark Gorenberg, Paul Kaminski, Art Samberg, Daniel Schwinn, Steve Isakowitz, and the Northrop Grumman Corporation.

Claudia Alemán, daughter of Visiting Committee member Miguel Alemán, showed her own generosity, endowing a professorship in the department with a $4 million gift. In late September 2017, Paulo Lozano was named the M. Alemán-Velasco Professor of Aeronautics and Astronautics.

The largest recent contribution is that of The Boeing Company, making a multi million–dollar gift in support of a new wind tunnel.

Department Awards

- Administrative assistant Robin Courchesne-Sato received the Wings Award, established to recognize an individual support staff member in AeroAstro for excellence.
- Senior administrative assistant Joyce Light received the Spirit of XVI Award, a recognition given to an individual or team in AeroAstro whose work, commitment, and enthusiasm contribute significantly to the achievement of the mission of the department.
- Graduate student Barret Schlegelmilch received the Vickie Kerrebrock Award, given in recognition of students, staff, faculty, and others (either individually or as members of a group) who have made significant contributions to building a sense of community.

Research

The department's total research expenditures (adjusted for duals) are as follows for FY2014, FY2015, and FY2016: $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 the Undergraduate Research Opportunities Program. In addition, research activities in other MIT laboratories and centers are open to students registered in AeroAstro.

Aerospace Computational Design Laboratory

The Aerospace Computational Design Laboratory's (ACDL) mission is the advancement and application of computational 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 the advancement of computational fluid dynamics for complex, three-dimensional flows, enabling significant reductions in time from geometry to solution. Specific research interests include aerodynamics, aeroacoustics, flow control, fluid–structure interactions, 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. 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 the solution of stochastic partial differential equations, 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 Partial Differential Equation (PDE)-constrained optimization, real-time simulation and optimization of systems governed by PDEs, multiscale and multi-fidelity optimization, model order reduction, geometry management, and fidelity management. ACDL applies these methodologies to aircraft design and to the development of tools for assessing aviation environmental impact.

ACDL faculty are professors Youssef Marzouk (director), David Darmofal, Mark Drela, Warren Hoburg, Jaime Peraire, Qiqi Wang, and Karen Willcox. Research staff include Steven Allmaras, Robert Haimes, Marshall Galbraith, and Ngoc Cuong Nguyen.

Aerospace Controls Laboratory

The Aerospace Controls Laboratory (ACL) researches autonomous systems and control design for aircraft, spacecraft, and ground vehicles as well as autonomous cars. Theoretical research is pursued in such areas as decision making under uncertainty; path planning, simultaneous localization and mapping (SLAM), activity, and task assignment; mission planning for unpersonned aerial vehicles; sensor network design; and robust, adaptive, and nonlinear control. A key aspect of ACL is the Real-Time Indoor Autonomous Vehicle Test Environment, also known as RAVEN, a unique experimental facility that uses a motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and aircraft, and robust coordination algorithms for multiple vehicles; and a ground projection system that enables real-time animation of the planning environment, beliefs, uncertainties, intentions of the vehicles, predicted behaviors (e.g., trajectories), and confidence intervals of the learning algorithms. Recent research is outlined below.

Crossmodal Reinforcement Learning

Intelligent agents should be capable of disambiguating local sensory streams to realize long-term goals. In recent years, the combined progress of computational capabilities and algorithmic innovations has afforded reinforcement learning (RL) approaches the ability to achieve this desiderata in impressive domains, exceeding expert-level human performance in durative tasks, such as Atari 2600 games and board games such as Go. Nonetheless, many of these algorithms thrive primarily in well-defined mission scenarios learned in isolation from one another; such monolithic approaches are not sufficiently scalable for missions where goals may be less clearly defined, and sensory inputs found salient in one domain may be less relevant in another. ACL researchers recently introduced the Crossmodal Attentive Skill Learner, a new framework for multisensory learning integrated with hierarchical RL to enable learning high-level policies that are transferable across tasks. This work provides concrete examples where the crossmodal attentive approach not only improves performance in a single task, but accelerates transfer to new tasks. Experiments demonstrate that the introduced crossmodal attention mechanism anticipates and identifies useful latent features, while filtering out irrelevant sensor modalities during execution. As a final contribution, the Arcade Learning Environment (a standard and popular Atari-based reinforcement learning benchmark) is modified to support audio queries, with evaluations conducted to show benefits of crossmodal learning in several games.

Decentralized Multi-task Learning

Many real-world tasks involve multiple agents with partial observability and limited communication. While our previous works improved multiagent planning scalability, they assumed knowledge of a high-level domain model (e.g., probabilistic models over sensors and actions). Learning without knowledge of the underlying model is challenging in these settings due to local viewpoints of agents, which perceive the world as nonstationary due to concurrently exploring teammates. Approaches that learn specialized policies for individual tasks face major problems when applied to the real world: not only do agents have to learn and store a distinct policy for each task, but in practice the identity of the task is often non-observable, making these algorithms inapplicable. This work formalizes and addresses the problem of multitask, multiagent reinforcement learning under partial observability. Our first contribution is a decentralized single-task learning approach that is robust to concurrent interactions of teammates. Our second contribution is an approach for distilling single-task policies into a unified policy that performs well across multiple related tasks, without explicit provision of task identity. Both the single-task and multitask phases of the algorithm are demonstrated to achieve good performance on a set of multiagent domains. Our approach makes no assumptions about communication capabilities and is fully decentralized during both learning and execution. To our knowledge, this is the first formalization of decentralized, multi-agent, multitask learning under partial observability.

Optimal Communication Planning for Distributed Loop Closure Detection

Multirobot, or cooperative, simultaneous localization and mapping (CSLAM) is an active area of research with a wide spectrum of applications that span from robotic search and rescue in challenging environments to navigating fleets of autonomous cars. Communication is a crucial aspect of the approach, without which CSLAM would simply reduce to decoupled copies of conventional SLAM. Due to the distributed nature of the problem, detecting inter-robot loop closures (i.e., distributed place recognition) necessitates sharing sensory data with other robots. A naive approach to data sharing can easily lead to a waste of mission-critical resources. ACL proposed a general resource-efficient communication planning framework for inter-robot loop closure detection that takes into account both the total amount of exchanged data and the induced division of labor between the participating robots. ACL researchers presented a fast algorithm for finding globally optimal data exchange policies, and provided theoretical analysis to characterize the necessary and sufficient conditions under which simpler, unidirectional strategies (so-called monologs) are optimal. Compared to other state-of-the-art approaches, our framework is able to verify the same set of potential inter-robot loop closures while exchanging considerably less data and influencing the induced workloads.

Socially Acceptable Navigation

Autonomous (i.e., self-driving) vehicles are increasingly being tested on highways and city streets. But there is also a need for robots that can navigate through other environments, such as sidewalks, buildings, and hallways. In these situations, the robots must interact and cooperate with pedestrians in a socially acceptable manner. The rules of the road no longer apply—there are no lanes or street signs and pedestrians don't use turn signals when cutting through crowds. ACL developed motion planning algorithms using deep reinforcement learning, in which simulated agents are rewarded for reaching their goal positions, and penalized for colliding with one another. Social norms, such as passing one another on the right and overtaking slower agents on the left are also encoded in the algorithm. These algorithms enabled a robot to navigate autonomously at human walking speed among the public through the first floor of the Stata Center (Building 32) for more than 20 minutes at a time without manual intervention.

Autonomy for Mobility on Demand

Self-driving campus shuttles are an emerging field of transportation. However, the adoption of this mobility on demand framework, for example on our MIT campus, requires a high quality of service. This implies to provide faster transportation than walking and a safe ride for the passengers and pedestrians. The ACL project Socially Acceptable Navigation has already developed a state-of-the-art framework that allows fast navigation of a small-scale robot in pedestrian environments. However, the learned navigation policy with reinforcement learning raises safety concerns. The policy implicitly fails to predict out-of-data pedestrian behavior, such as a person with a leg injury, and outputs a possibly unsafe driving behavior. We leverage new advances from Bayesian deep learning to track the model uncertainty and adapt for a more conservative driving behavior around out-of-data pedestrians. ACL also converts a golf cart into a fully autonomous vehicle, to test the motion planning algorithms and previous research in mobility on demand routing.

Transferable and General Model of Pedestrian Motion Prediction

Intention recognition of pedestrians is crucial to safe and reliable working of autonomous vehicles, when serving as, for instance, indoor service robots or self-driving cars in busy urban areas. We propose a context based model of motion prediction to predict pedestrian behaviors at crowded intersections (titled CASNSC). We incorporate semantic features from the environment to improve the prediction of pedestrian trajectories at intersections and busy streets. Adding the environmental context, when available, not only makes prediction more robust but can also provide increased flexibility of prediction in new environments. Given some prior knowledge of the curbside geometry, we provide a transferable framework (titled TASNSC), that can accurately predict pedestrian trajectories, even in new intersections that it has not been trained on. This is achieved by making use of the contravariant components of trajectories in the curbside coordinate system, which ensures that the transformation of trajectories across intersections is affine, regardless of the curbside geometry. Furthermore, the proposed model can be generalized to different domains with different geometry, which enables us to either collectively or incrementally learn as and when we observe new data. We also have two different data collection platforms to record data from cameras and lidar sensors and provide a large pedestrian dataset. We demonstrate improvement in prediction accuracy in the case of the same train and test intersections. Furthermore, we show a comparable prediction performance of TASNSC when trained and tested in different intersections with the baseline, trained and tested on the same intersection.

Integrated Drone Station

This project will create a planning framework for a fleet-wide package delivery system that accounts for the unpersonned aerial vehicle (UAV) dynamics and capabilities (time varying), the battery models and real-time charge state, the external disturbances, and the package demand models and on-demand needs (e.g., delivery location, package size, and when needed). These challenges lead to complex planning problems for which efficient algorithms are needed to replan in real time to provide solutions that best utilize the team of ground and air vehicles for the various delivery, recharge, and transport tasks that must be performed. Our algorithms should help lead to the high quality of service that will be crucial for creating an economically viable first/last mile delivery system.

Context and Task-Aware Active Perception

Reasoning about uncertainty is essential for an autonomous agent to behave optimally in an uncertain environment. Partially Observable Markov Decision Process (POMDP) is a framework that enables a tradeoff between exploration and exploitation in a principal way. While POMDP has been successfully applied to robust planning, control, and learning, active perceptions in environments involving human agents have seldom been investigated. ACL will develop algorithms based on POMDP for an autonomous agent to actively interact with humans. These algorithms are expected to efficiently identify human intents and utilize this information for better decision making.

Decentralized Dynamic Task Allocation for Mobile Robots

In time-sensitive and dynamic missions, multi-UAV teams must respond quickly to new information and objectives. Previous methods require fully resolving the initial task allocation team, which can be prohibitively slow especially in highly dynamic environments and poor communication settings. To respond to new tasks, we develop algorithms that can reuse information and solutions, modifying existing allocations, to allocate new tasks. Specifically, the consensus-based bundle algorithm with partial replanning (CBBA-PR), a decentralized task allocation algorithm, by allowing for the fast allocation of new tasks without a full reallocation of existing tasks. CBBA-PR enables the team to tradeoff between convergence time and increased coordination by resetting a portion of their previous allocation at every round of bidding on tasks. By resetting the last tasks allocated by each agent, we are able to ensure the convergence of the team to a conflict-free solution. CBBA-PR can be further improved by reducing the team size involved in the replanning, further reducing the communication burden of the team and runtime of CBBA-PR.

Range Corrector Method for the Space Shuttle Entry Guidance Algorithm

ACL has designed a space shuttle entry guidance with an extended analytic range corrector method. The guidance method is a variation of shuttle entry guidance in which the parameters that define the drag profile are modified using quadratic splines to make the drag profile smooth and easier to customize. To account for off-nominal entry conditions and ensure the vehicle flies the correct range to the runway, the nominal reference drag profile is modified online utilizing analytic expressions for the derivative of range with respect to the relevant drag profile parameter. This project addresses problems when the vehicle is highly constrained and can easily violate constraints, such as heat load and heat rate constraints, due to small drag profile variations. The methods by which the drag profile is updated are changed in order to provide multiple perturbation options. In providing multiple drag profile update parameters, a memoryless range error allocator is implemented with a vector of weights as a design variable. The resulting algorithm seeks to leverage the high technology readiness levels shuttle entry guidance routine by making minimal modifications to the implementation, while increasing robustness to entry interface dispersions under tight heating constraints.

Defense Advanced Research Projects Agency Fast Lightweight Autonomy

The goal of the Fast Lightweight Autonomy program is to develop robust, real-world autonomy for small quadrotor-style drones in GPS-denied, tactically-relevant environments. As one of three participating teams, the Draper-MIT team was tasked specifically with developing a platform and algorithms for operation in outdoor urban environments. The ACL's contributions to the platform were multifold: a set of novel control and planning algorithms for high-speed obstacle avoidance with limited sensing in unknown environments, development and robustification of a visual-inertial state estimator that allowed for accurate localization over long (>500m) GPS-denied missions, and the development of a robust, vision-based system for localization for semantic objects such as cars, military vehicles, and doors. These systems were demonstrated successfully at a series of milestone events, and the team has been invited to a final VIP demonstration this coming fall.

ACL faculty are Jonathan How and Steven Hall.

The 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 Robotics (MERS) group, and Roy's Robust Robotics Group are part of the Computer Science and Artificial Intelligence Lab (CSAIL). 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.

Operating Autonomous Vehicles to Maximize Utility in an Uncertainty Environment

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 they no longer can be met. Companies like the MIT spin-off Terrafugia offer vehicles that can fly between local airports and can travel on local roads. To operate these innovative vehicles, one must be trained as a certified pilot, thus limiting the population that can benefit from this innovative concept.

In collaboration with Boeing, MERS has demonstrated in simulation the concept of an autonomous personal air vehicle in which the passenger interacts with the vehicle in the same manner as they interact today with a taxi driver.

Human-Robot Interaction Between an Astronaut and the Athlete Lunar Rover

MERS has developed methods for controlling walking machines, guided by qualitative snapshots of walking gait patterns. These control systems achieve robust walking over difficult terrain by embodying many aspects of a human's ability to restore balance after stumbling such as adjusting ankle support, moving free limbs, and adjusting foot placement. Members of the MERS group applied generalizations of these control concepts to control the JPL Athlete robot, a six-legged/wheeled lunar rover that performs heavy lifting and manipulation tasks by using its arms and legs.

Communications and Networking Research Group

The Communications and Networking Research Group's (CNRG) primary goal is the design of network architectures that are cost effective, scalable, and meet emerging needs for high data rate and reliable communications. Over the past year, members of CNRG authored over a dozen journal papers in first tier journals and a similar number of conference papers in highly selective peer-reviewed conferences. Moreover, their works received the best paper awards at IEEE Infocom 2018 and ACM MobiHoc 2018—two premier conferences in the networking field. Their contributions included the design of transmission scheduling schemes that optimize information freshness in wireless networks, the design of network control algorithms for networks in adversarial environments, and the study of robustness in interdependent networks.

Future internet of things applications will increasingly rely on the exchange of delay sensitive information for monitoring and control. Application domains such as autonomous vehicles, command and control systems, virtual reality, and sensor networks, rely heavily on the distribution of time-critical information. Age of information

(AoI) is a recently proposed metric that captures the freshness of the information from the perspective of the application. AoI measures the time that elapsed from the moment that the most recently received packet was generated to the present time. Over the past few years, CNRG has been developing network algorithms for optimizing AoI in wireless networks. This past year, two papers authored by CNRG members on this topic received best paper awards from leading conferences in the field. In particular, the paper, "Optimizing Age of Information in Wireless Networks with Throughput Constraints," by Igor Kadota, Abhishek Sinha, and Eytan Modiano, received the 2018 IEEE INFOCOM Best Paper Award, and the paper, "Optimizing Information Freshness in Wireless Networks under General Interference Constraints," by Rajat Talak, Sertac Karaman, and Eytan Modiano, received the 2018 ACM MobiHoc Best Paper Award.

Over the past decade CNRG developed a number of network control algorithms for communication networks, where the objective is usually to maximize network throughput or utility. The effectiveness of these algorithms usually relies on the premise that the network dynamics are stochastic. However, increasingly networks operate in environments where the network dynamics are non-stationary or even adversarial. For example, modern communication networks frequently suffer from distributed denial-of-service attacks or jamming attacks, where traffic injections and channel conditions are controlled by some malicious entity in order to degrade network performance. Over the past year the group developed network control algorithms that optimize network performance in adversarial settings. In particular, the group developed network routing and scheduling schemes that provide guaranteed performance under worst-case (adversarial) network dynamics.

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, transportation networks, and so forth. 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, where 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 studied the interdependence between power grid and communication networks and developed power grid control algorithms that are robust to interdependence failures.

In recent years the group has been pursuing industrial collaborations in order to increase the impact of their work on practical systems. Over the past year, the group collaborated with researchers at Nokia Bell-Labs on the problem of resource allocation in distributed computing networks. In addition, the group has a joint project with BBN Technologies on resilient overlay networks, a project with Qualcomm on mission critical communications, and 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, queueing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Gas Turbine Laboratory

The Gas Turbine Laboratory's (GTL) mission is to advance the state of the art in fluid machinery for power and propulsion. GTL research is focused on advanced propulsion and energy systems and turbomachinery. Activities include computational, theoretical, and experimental study of the following:

- 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 and aero-acoustic
- Novel aircraft and hybrid-electric propulsion system concepts for reduced environmental impact
- Multiphase and nonideal 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 who are leaders in this field. For example, GTL has collaborative projects with major American aeroengine manufacturers, as well as European and Japanese companies, so that there are many connections between the work in the GTL and real-world problems. Research support also comes from the US National Aeronautics and Space Administration (NASA) centers. In addition to in-house experimental work, research is also 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, where the GTL developed an advanced commercial aircraft configuration with a boundary layer ingesting, embedded propulsion system dubbed the double bubble D8 concept.

In summary, the Gas Turbine Laboratory participates in research topics related to short-, mid-, and long-term problems, and maintains strong ties with industry and government research in the areas of propulsion and turbomachinery technology, as well as with other academic institutions who are leaders in this field.

Faculty and research staff include David Darmofal, Fredric Ehrich, Alan Epstein (professor emeritus), Edward Greitzer, Zoltán Spakovszky (director), Jayant Sabnis (senior lecturer), David Hall (research engineer), and Choon Tan (senior research engineer).

Human Systems Laboratory

The Human Systems Laboratory (HSL; formerly the Man Vehicle Lab), performs research to improve the understanding of human physiological and cognitive capabilities to optimize human-system effectiveness and to develop appropriate countermeasures and evidence-based engineering design criteria. Research is interdisciplinary, using techniques from biomechanics, sensory-motor physiology, human performance assessment, human factors engineering, signal processing, artificial intelligence, and biostatistics. These methods are applied to space suit and exoskeleton design, wearable and virtual/augmented reality technologies, planetary mission resource utilization, space teleoperation, astronaut and pilot disorientation, artificial gravity, automation and autonomy, human-system task modelling, and display and control design. Systems evaluated include exoskeletons, aircraft, spacecraft, cars, and railroads. HSL faculty and students have flown experiments on parabolic flight, numerous space shuttle missions, the Russian MIR station, and the International Space Station (ISS); founded and led the National Space Biomedical Research Institute; and are helping NASA's Human Research Program develop biomedical countermeasures for ISS as well as participating in various planetary science missions (e.g., the MOXIE experiment on Mars 2020).

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 control and training. Ongoing work includes the computational modeling of human-spacesuit interaction, development 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 g environments using a centrifuge at the Massachusetts Eye and Ear Infirmary, and a study with University of California at Davis on customized and just-in-time space telerobotics refresher training. Non-aerospace projects include General Electric Company 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 decision making in medical and military environments; and the development of co-adaptive exoskeleton systems.

Research sponsors include NASA; the National Space Biomedical Research Institute; the National Science Foundation; the Office of Naval Research; the Natick Soldier Research, Development, and Engineering Center; the Federal Aviation Administration (FAA); the Department of Transportation Federal Railway Administration; Draper Laboratory; the Center for Integration of Medicine and Innovative Technology; the Deshpande Center for Technological Innovation; Lincoln Laboratory; and the MIT Portugal Program. The laboratory also collaborates with the Volpe Transportation Research Center; Aurora Flight Sciences; Massachusetts General Hospital; and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

HSL faculty include Professors Jeffrey Hoffman and Leia Stirling (co-directors), Professor Dava Newman; Professor Emeritus Laurence Young; Senior Lecturer Charles Oman, and Professor Julie Shah. HSL faculty teach courses in human systems engineering, probability and statistics, space systems engineering, transport aircraft systems, space policy, flight simulation, aerospace biomedical and life support engineering, and leadership. The HSL faculty also serve as director for the HST Graduate Program in Bioastronautics (Newman), director of the Massachusetts Space Grant Consortium (Hoffman), participate in the NASA Translational Research Institute for Space Health (Young and Hoffman), are members of the National Academies' Transportation Research Board Railroad Operational Safety Committee (Oman), and the American Society for Testing and Materials F48 Committee on Exoskeletons and Exosuits (Stirling).

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 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, and Amedeo Odoni, and Peter Belobaba (principal research scientist).

Laboratory for Aviation and the Environment

A defining challenge for the aviation industry is to address aviation's environmental impact. Laboratory for Aviation and the Environment (LAE) research sets out to support this mission by improving our understanding of aviation's impact on air quality and climate change, supporting the implementation of aviation policy aimed at mitigating environmental impact, and developing and analyzing technology to reduce aviation emissions. In particular, LAE researchers are developing and assessing operational, regulatory, and technological mitigation options and disseminating knowledge and tools that 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 understand and analyze 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 lifecycle and technoeconomic 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., FAA and International Civil Aviation Organization) about the costs and benefits of aviation policies. Thus, research at LAE directly contributes to defining global and domestic aviation policy.

A current focus in tool development at LAE is on developing a model for understanding contrails' climate impact. Contrails are the white line-shaped clouds that form behind aircraft and are considered to be the potentially single 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 have developed a novel electric aircraft propulsion system without moving parts, which has been 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 impact in the US and Singapore.

LAE faculty and staff include Steven Barrett (director), Ray Speth (associate director), Florian Allroggen (laboratory executive officer), Jayant Sabnis, Hamsa Balakrishnan, R. John Hansman, Ian Waitz, Karen Willcox, and Mark Staples (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 back 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 (Building 32), 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 Luca Carlone, Emilio Frazzoli, Jonathan How, Sertac Karaman, Eytan Modiano, and Moe Win.

The Learning Laboratory

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

Robert C. Seamans Jr. Laboratory

The Seamans Laboratory occupies the first floor, and includes the Concept Forum and the Al Shaw Student Lounge. The Concept Forum is a multipurpose room for meetings, presentations, lectures, videoconferences, collaboration, distance learning, and informal social functions. In the forum, students work together to develop multidisciplinary concepts, and learn about program reviews and management. The Al Shaw Student Lounge is a large, open space for social interaction and operations.

Arthur and Linda Gelb Laboratory

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

Gerhard Neumann Hangar

The Gerhard Neumann Hangar is a high bay space with an arching roof. This space lets students work on large-scale projects that require 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.

necstlab

The Nano-Engineered Composite Aerospace Structures Lab (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 (MEMS) topics. The necstlab group has interests that span from fundamental materials synthesis (e.g., novel catalysts for carbon nanostructure synthesis) through 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 to create higher-performance advanced composites using nanotechnology. Beyond the NECST Consortium members, necstlab research is supported directly or through collaboration by industry, Air Force Office of Scientific Research, Army Research Office, NASA, National Institute of Standards and Technology, National Science Foundation, Office of Naval Research, and others.

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

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

In fall 2014, the group moved into new laboratory space in Building 35. Examples of current and past research projects include the following:

- Efficient deicing of aircraft wings with integrated carbon nanotube-based heaters
- Out-of-autoclave curing of composites with aligned carbon nanotube heating
- Bio nano electromechanical 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

necstlab faculty include Brian Wardle (director), John Dugundji (professor emeritus), and Antonio Miravete (visitor).

Space Propulsion Laboratory

The Space Propulsion Laboratory (SPL) studies and develops systems for increasing performance, and reducing costs of space propulsion and related technologies. A major area of interest to the lab is electric propulsion, in which electrical, rather than chemical energy propels spacecraft. The benefits are numerous; hence the reason electric propulsion systems are increasingly applied to communication satellites and scientific space missions. These efficient engines allow 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, 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 (like 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, for example, the use of highly monenergistic molecular ion beams in focusing columns for materials structuring and characterization at the nanoscale and also applications in vacuum technology.

A newer area of research for SPL, beyond space propulsion, is the exploration of new applications of plasma science and technology in aerospace. The research topics include the following:

- Analytical and numerical modeling of the interaction of lightning with aircraft, including aircraft-triggered leader inception models and swept stroke physics. Studies include fundamental aspects of gas discharge physics and their transitions, integration studies of how a lightning arc interacts with an aircraft in flight, as well as new concepts for protection and avoidance.
- Non-equilibrium plasma applications, including plasma-assisted combustion and plasma-assisted aerodynamics

SPL facilities include a computer cluster where plasma and molecular dynamics codes are routinely executed and a state-of-the-art laboratory including five vacuum chambers, clean room environment, electron microscope, materials synthesis capabilities, nanosatellite qualification equipment (vibration/thermal and in-vacuum magnetically-levitated CubeSat simulator), plasma/ion beam diagnostic tools to support ongoing research efforts, high voltage equipment, and a laser micromachining facility.

SPL faculty are Paulo Lozano (director), Carmen Guerra-Garcia, and Manuel Martinez-Sanchez (emeritus).

Space Systems Laboratory

Space Systems Laboratory (SSL) research contributes to the exploration and development of space. SSL's mission is to explore innovative space systems concepts while training researchers to be conversant in this field. The major programs include systems analysis studies and tool development, AeroAstro student-built instruments and small satellites for exploration and remote sensing, precision optical systems for space telescopes, and microgravity experiments operated aboard the 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, as well as formation flight. The SPHERES facility consists of three satellites 20 centimeters in diameter that have been aboard the International Space Station since May 2006. In 2009, SSL expanded the uses of SPHERES to include science, technology, engineering, and mathematics education (STEM) outreach through an exciting program called Zero Robotics, which engages high school and middle school students in a competition aboard the ISS using SPHERES. It has expanded to more than 100 US and 50 European teams annually. The finals of the competition run aboard the ISS by Russian cosmonauts, and astronauts from the US and the European Space Agency.

There have been more exciting hardware augmentations to SPHERES. Based on the Visual Estimation for Relative Tracking and Inspection of Generic Objects (VERTIGO) program, a cadre of Universal Docking Ports and Halos (or expansion ports) are now aboard the ISS and awaiting operations. The Universal Docking Ports enable active docking and undocking of the satellites creating a rigid assembly; they add fiducial-based vision navigation. The Halo structure enables attachment of up to six electro-mechanical devices around a single SPHERES satellite, allowing researchers to study complex geometrical system reconfiguration.

SSL has designed, built, tested, and delivered the Regolith X-ray Imaging Spectrometer (REXIS) student collaboration instrument to NASA's next New Frontiers mission: Origins, Spectral Interpretation, Resource Identification, Security Regolith Explorer (OSIRIS-REx). The mission is an asteroid sample return mission that launched on September 8, 2016 to visit the near-earth asteroid Bennu, and is scheduled to return to Earth in 2023. REXIS is one of five instruments onboard and uses a two by two array of Lincoln Laboratory–designed charged-coupled devices to measure the X-ray fluorescence from Bennu to 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 MIT Earth, Atmospheric and Planetary Sciences (EAPS) and AeroAstro appointment, and Rebecca Masterson are leading the project in collaboration with EAPS, the MIT Kavli Institute for Astrophysics and Space Research, and 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 to the OSIRIS-REx spacecraft in December 2015. The REXIS student team supported Assembly, Test, and Launch Operations at Lockheed Martin and wrapped up testing at Kennedy Space Flight Center.

SSL is directed by David Miller. Kerri Cahoy, Jeffrey Hoffman, Olivier de Weck, and Richard Binzel participate in multiple SSL projects. Rebecca Masterson manages REXIS. Danilo Roascio leads the SPHERES team. The group is supported by fiscal officers Suxin Hu, Kim Ngan Le, and administrative assistant Marilyn E. Good. Collaborators include Manuel Martinez-Sanchez, Paulo Lozano, and Sara Seager (EAPS).

Space Telecommunications, Radiation, and Astronomy Laboratory

The Space Telecommunications, Radiation, and Astronomy Laboratory, or STAR Lab, is part of the Space Systems Lab. The lab focuses 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) that is constantly streaming toward Earth from the sun. This includes development of several small, shoebox- and backpack-size satellites, called CubeSats, for weather sensing and technology demonstration work, particularly in laser communications, as well as work on much larger, Hubble-size space telescopes for direct imaging of exoplanets.

Weather Sensing CubeSat Projects

Microsized Microwave Atmospheric Satellite

Microsized Microwave Atmospheric Satellite (MicroMAS) was MIT's first student shoebox-size 3U CubeSat, in collaboration with William Blackwell at MIT 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 MIT Lincoln Laboratory, we have built two MicroMAS-2 CubeSats.

Microwave Radiometer Technology Acceleration mission

Microwave Radiometer Technology Acceleration mission (MiRaTA), sponsored by the NASA Earth Science Technology Office, is a joint effort between Lincoln Laboratory, the Aerospace Corporation, the University of Massachusetts at Amherst, and the Space Dynamics Laboratory. The 3U CubeSat has a temperature-mapping, tri-band microwave radiometer as well as a GPS radio occultation payload, which makes temperature and pressure profile measurements. MiRaTA launched from a Delta II rocket carrying Joint Polar Satellite System-1 in November 2017 from Vandenberg Air Force Base.

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) project was selected by NASA's Earth Venture Instrument program, and will be part of the MIT 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

STAR Lab is working with a commercial partner who builds and flies 3U CubeSats to include our laser communications system for demonstration. The Nanosatellite Optical Downlink Experiment makes use of a MEMS fast steering mirror to achieve precise pointing for laser communications, increasing data rates and improving efficiency and security, all without the regulatory overhead of high bandwidth radio systems.

Deformable Mirror Demonstration Mission

The Deformable Mirror Demonstration Mission (DeMi) will fly a MEMS deformable mirror and compact wavefront sensor on a 6U CubeSat in low Earth orbit, to characterize mirror performance. These MEMS deformable mirrors can play key roles in wavefront control systems on larger space telescopes to enable 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 of Boulder, CO, who are building the bus.

Free-space Lasercom and Radiation Experiment

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

Bigger Space Telescopes for Exoplanet Science

Kerri 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. The group is part of the science investigation team for the Wide Field Infrared Survey Telescope mission, which will have a wavefront control system and an internal coronagraph on a Hubble-size space telescope. We also support exoplanet mission science and technology definition teams, such as Exo-C and HabEx.

System Architecture Laboratory

Every built system has an architecture. Products such as communications satellites, automobiles, semiconductor capital equipment, and commercial aircraft are defined by a few key decisions that are made early in each program's lifecycle. The emerging field of system architecture aims to understand what patterns emerge across disparate domains to gain an understanding of what makes good architecture.

In the System Architecture Lab (SAL), we study the early-stage technical decisions that will determine the majority of the system's performance. We've helped architect systems from lunar surface exploration vehicles to oil exploration platforms for ice-bound drilling. Past research partners and sponsors include Facebook, SES, Sikorsky, NASA, Pratt & Whitney, Boeing, BP, Caterpillar, AMGEN, Verizon, and Amazon.

The System Architecture Lab's work is divided into five research areas:

- System Architecture Methods and Computational Tools
- Space Communications
- Architecting Space Exploration
- Stakeholder Analysis Methods and Tools
- Commonality and Platforming

Recent research highlights include renewed partnership with Facebook to study internet connectivity for the four billion people who do not have access today, comparing a broad range of options from satellite internet, to high and low tethered platforms, to point to point networks on the ground. Additionally, the SAL has a new partnership with communications satellite operator SES to study dynamic resource allocation algorithms for managing satellite utilization, a joint venture between AeroAstro and CSAIL.

SAL has launched a MOOC (massive open online course) on architecture and system engineering, which has brought together 4,200 participants over the last two years from the US Navy, Ford Motor Company, General Motors, General Electric Company, and Boeing.

The System Architecture Lab was founded by Edward Crawley and its director is Bruce Cameron.

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 their lifecycle value. The Systems Engineering Research Group (SERG) focuses on research in systems engineering and technology management for long-lived 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 2.5 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. The so-called HabNet is a new space habitation modeling and simulation environment that quantifies the flow of resources such as water, gases, propellants, food, spares, and crew through closed or semi-closed habitat systems. Our projects in the AY2018 expanded the work of the lab into the area of in-space manufacturing with a grant from the NASA Office of Emerging Space. In this study, 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 or 1,000m^2 at a cost of approximately $438/W. We also contributed to the winning submissions of the 2017 NASA Revolutionary Aerospace Systems Concepts–Academic Linkage graduate competition on the topic of an evolvable space hotel together with the MIT Department of Architecture.

A newer direction for SERG is the study of distributed satellite missions for Earth science under uncertainty, as well as the modular design of platform-based systems for future aerospace and defense applications. As part of the NASA Goddard Space Flight Center project Tradespace Analysis Tool for Constellations, SERG contributes to a capability for architecting future distributed Earth science missions. The integrated analysis of multi-spectral satellite imagery for systems modeling of terrestrial infrastructure is part of the current ambitions of SERG. A recent master's thesis developed a refined algorithm for detection of buildings, road segments, and solar arrays from satellite and aerial imagery.

In the related area of system design under uncertainty, we are also developing a systems model of an autonomous vehicle, thanks to a grant from Hitachi Systems, in order to quantify the trade-offs between recognition accuracy, latency, and hardware costs. This decision-support tool will enable a rationalized choice of sensors and processors on autonomous vehicles as a function of the operational environment.

Additionally, we have been tasked by NASA headquarters with the development of a roadmap for commercial space technology. This roadmap includes key enabling technologies such as in-space manufacturing, space tourism, and commercial grade space imagery that are not captured by the existing technology area roadmaps.

Awards and recognitions received in AY2018 include the election of Professor de Weck as a Center of Excellence on Systems Architecture, Management Fellow (December 2017) and an International Council on Systems Engineering Distinguished Service Award (June 2018) for his five-year service as editor-in-chief of the journal *Systems Engineering*.

The Strategic Engineering Research Group is directed by de Weck, who is currently on leave from MIT as senior vice president for Technology Planning and Roadmapping at Airbus. He will return to MIT in January 2019. Associate directors of the Strategic Engineering Research Group are Afreen Siddiqi, Bryan Moser, and Eric Rebentisch.

System Engineering Research Lab

The increasingly complex systems we are building today enable us to accomplish tasks that were previously difficult or impossible. At the same time, they have changed the nature of accidents and increased the potential to harm not only life today but also in 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 system in which our systems are designed and operated.

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

- 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 cultural, social, and legal systems on 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 cybersecurity and physical (nuclear) security in work for the US Department of Defense, FAA, and US Department of Energy.

The System Engineering Research Lab is directed by Nancy Leveson. John Thomas is a System Engineering Research Lab-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 base and understanding that will help facilitate and accelerate advanced materials systems development and use in various advanced structural applications and devices.

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

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

In supporting this work, TELAMS has complete facilities for the fabrication of structural specimens such as coupons, shells, shafts, stiffened panels, and pressurized cylinders made of composites, active, and other materials. TELAMS testing capabilities include a battery of servohydraulic machines for cyclic and static testing, a unit for the catastrophic burst testing of pressure vessels, and an impact testing facility.

TELAMS maintains capabilities for environmental conditioning, testing at low and high temperature, and in hostile and other controlled environments. There are facilities for microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization. This includes ties to ability for computer microtomography.

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

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

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, ultrawideband 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, design of efficient cooperative localization algorithms, and development of realistic localization systems tested via network experimentation. The system design relies also on channel models obtained through a state-of-the-art apparatus built by the team for automated channel measurements over a range of 2 to 18 GHz. It is unique in that extremely wideband signal measurements, more than twice the bandwidth of conventional ultrawideband 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 unpersonned aerial vehicle networks. They also proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and interference engineering.

To advocate outreach and diversity, the group is committed to attracting undergraduates and others from underrepresented minority groups, giving them exposure to theoretical and experimental research at all levels. For example, the group has a strong track record for hosting students from both the Undergraduate Research Opportunities Program and the MIT Summer Research Program. Professor Win, the director of the WINSLab, maintains dynamic collaborations and partnerships with academia and industry, including the University of Bologna and Ferrara in Italy, University of Lund in Sweden, University of Oulu in Finland, King Abdullah University of Science and Technology in Saudi Arabia, Kyung Hee University in Korea, Singapore University of Technology and Design, Tsinghua University in China, Draper Laboratory, the Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

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, the aeroelastic dynamics of airport control tower configurations for the FAA, and the less anticipated live tests in Olympic ski gear, space suits for tare evaluations related to underwater simulations of weightless space activity, racing bicycles, subway station entrances, and Olympic rowing shells for oarlock system drag comparisons.

In its 80 years of operation, Wright Brothers Wind Tunnel work was been recorded in hundreds of theses and more than 1,000 technical reports.

In February, it was announced that AeroAstro will replace the venerable 80-year-old Wright Brothers Wind Tunnel with the largest and most advanced academic wind tunnel in the United States. The new tunnel will:

- Permit increased test speeds from the current 150 miles per hour to 200 miles per hour
- Greatly improve research data acquisition
- Halve the power requirements of the original 2,000 horsepower fan motor
- Increase test section volume from 850 cubic feet to 1,600 cubic feet, and test section area from 57 square feet to 80 square feet
- Improve the ability to test autonomous vehicles and aerodynamic components including wings, bodies, and wind turbines
- Enable new MIT classes in advanced aerodynamics and fluid mechanics

To facilitate construction of the new tunnel and ongoing operations, Boeing made a funding pledge to become the lead donor of this $18 million project. It is anticipated the project will be completed in 2020.

Wright Brothers Wind Tunnel faculty and staff include Mark Drela and David Robertson (technical instructor).

Degree Programs

The bachelor of science 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). 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. What's more, the flexible degree program builds on the department's strength in collaborative, multidisciplinary problem solving. The Course 16-ENG degree programs offer 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 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.

Unified Engineering, the department's sophomore-level introduction to the foundations of aerospace engineering has been modified to better focus on four individual disciplines with the following subjects: 16.001 Materials and Structures, 16.002 Signals and Systems, 16.003 Fluids, and 16.004 Thermodynamics. 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[J] Robotics: Science and Systems, which can be used to fulfill the laboratory and CI-M requirements. This provides a new alternative in autonomous systems to our traditional design subjects in aircraft and spacecraft systems.

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 (CSE) doctoral degree, administered by the Center for Computational Engineering. Students enrolled in the AeroAstro CSE program can specialize in a computation-related aerospace field through focused coursework and a doctoral thesis.

Graduate Enrollment, 2010–2018

Academic year	2010	2011	2012	2013	2014	2015	2016	2017	2018
Graduate student body total	**226**	**226**	**229**	**246**	**241**	**233**	**228**	**223**	**230**
SM*	130	111	121	125	117	107	111	107	111
PhD**	96	115	108	121	124	126	117	116	119
Underrepresented minorities SM	9	7	9	12	13	17 (16%)	18 (16%)	11 (10%)	12 (11%)
Underrepresented minorities PhD	4	6	5	6	5	5 (4%)	4 (3%)	4 (3%)	8 (7%)
Women SM	30	22	21	23	23	26 (24%)	25 (23%)	22 (20%)	22 (20%)
Women PhD	17	20	16	22	26	25 (20%)	22 (19%)	17 (15%)	23 (19%)

Note: Numbers based on fifth-week enrollment data.

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

** Students who have passed the doctoral qualifying exam.

Undergraduate Enrollment, 2008–2018

Academic year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Sophomores	57	74	57	51	45	66	71	56	47	50	49
Juniors	66	55	65	47	46	43	53	65	54	43	47
Seniors	66	62	58	68	47	45	44	56	65	60	46
Totals	**189**	**191**	**180**	**166**	**138**	**154**	**168**	**177**	**166**	**153**	**142**
Women	30%	30%	34%	29%	31%	37%	36%	36%	35%	30%	34%
Underrepresented minorities	14%	32%	40%	28%	38%	30%	31.5%	32%	34%	15%	27%

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