Cover: The MIT Rocket Team with Therion. The rocket is 12 feet tall, 6 inches in diameter and designed to reach an altitude of 10,000 feet with its powerful solid motor capable of producing 760 pounds of thrust for more than three seconds. Therion’s fully-custom composite structure experiences more than 14Gs of acceleration as it reaches velocities surpassing 700 mph. For more on the team see the special Student Projects section of this AeroAstro issue. (MIT Rocket Team photograph)
Dear Friends,

Welcome to the 2016 issue of AeroAstro. In this, our 13th annual issue, you’ll find articles about our research; an interview with one of our terrific alumni; four pieces written by our students about unique projects with which they’re involved; updates on two of our iconic facilities, Building 31 (long-time home of the Gas Turbine Lab) and the Wright Brothers Wind Tunnel; a look at a new generation of AeroAstro innovators; and reports from 20 of our labs and centers. In short, this publication represents the core of what makes the department thrive: our research, our passions, and our people.

Renovations to Building 31 are well underway, with the building expected to be back on line by fall 2017. The finished project, which will include a new 3200 sq. ft. high bay space with 24-foot high ceilings and a motion capture system to test autonomous flying vehicles, will give us the opportunity to conduct research heretofore impossible. The building, which will be connected to the Ronald McNair Building (Building 32) via a bridge on the third floor, will include a 4,800 sq. ft. deck to allow outdoor flying tests. The renovated building will also house Beaver Works 2.0, a joint, flexible maker space shared by Lincoln Lab and the department. For more on Building 31 renovations, please read the article “Like a phoenix, Building 31 is reborn and rises — spectacularly” in this issue.

Academic year 2015-2016 marked the first time the department partnered with our colleagues in Electrical Engineering and Computer Science to offer enhanced Undergraduate Research Opportunities known as SuperUROPs. Combining a yearlong research project under the direct supervision of a faculty member and an industry mentor, with coursework focused on engineering communications, entrepreneurship, and ethics, the SuperUROP provides undergraduate students with a deep research experience as well as a head start on what will likely be their graduate school and/or industry future. Sixteen AeroAstro students successfully completed the SuperUROP program, and we look forward to even greater success in the coming year.

After a year’s hiatus, the department again hosted the Women in Aerospace Symposium, this year with special co-host Stanford University. Featuring keynote talks by NASA Deputy Administrator Dava Newman and Harvard University Fred Kavli Professor of Computer Science Radhika Nagpal, the symposium brought 23 of the brightest and best young women in the field to MIT to present their work. Presentations ran the gamut from “Atmospheric Impacts of Aviation Emissions,” to “Communication Strategies for Human-Robot Team Coordination,” to “Secure Estimation for Unmanned Aerial Vehicles against Adversarial Attacks,” and were, without exception, excellent. With plans to hold next year’s event on the West Coast, the MIT-Stanford Women in Aerospace Symposium is thriving.

One of the most anticipated events of the year was the visit of Jim Lovell (Capt., USN, Ret.) of Gemini 7 and 12, Apollo 8, and, most notably, Apollo 13. Speaking to a standing-room only crowd, Capt. Lovell presented the talk “A Successful Failure,” sharing details of the ill-fated Apollo 13 mission, which he commanded. The audience was enraptured. Feedback we received included: “It was one of the most inspiring talks I have heard — real engineering”; “Lovell was a captivating speaker, and the topic both dear to my heart and timeless. I will remember this as one of the best perks of being at MIT”; “Having had the chance to hear the events and experience directly from him was unforgettable and unique,
an absolute highlight.” Our undergraduates were fortunate to secure Capt. Lovell as the special guest for their annual AIAA Student-Faculty Dinner, at which he graciously participated in a fascinating Q&A session.

Another highlight of the year was our second annual trip to the West Coast with our sophomore Unified Engineering class. Over a whirlwind three days we visited Boeing, Northrup Grumman, Lockheed Martin’s Skunk Works, NASA’s Jet Propulsion Laboratory, SpaceX, and Virgin Galactic.

As you might imagine, it’s never dull here. One day we’re touring JPL with our sophomores, the next day we’re in conference with industry partners negotiating a research agreement. And, of course, in the meantime, we mentor freshmen advisees, counsel upperclassmen, deliberate on committees, work on our own research, etc. Our students are equally busy, if not more so. There is no “typical day” in the life of AeroAstro, and, for that, we are grateful. As we continue to grow and change, we’re excited at the prospects of tomorrow.

Thank you for reading and we welcome your feedback. Let us know what you think. Our doors are always open.

JAIME PERAIRE
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When NASA's OSIRIS-REx rendezvous with the asteroid Bennu in 2019, its MIT student-designed REgolith X-ray Imaging Spectrometer will provide researchers with vital data on the asteroid's composition. (NASA illustration)
OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer) is one such New Frontiers mission, launched on September 8, 2016. The OSIRIS-REx spacecraft will travel through interplanetary space for 2.5 years to rendezvous with the near-Earth asteroid, Bennu. The spacecraft will make a reconnaissance study of the roughly 492 meter (1,614 foot) diameter asteroid using a suite of instruments, select a sampling site, take a sample of the asteroid regolith, and return the sample to Earth.

One of the five instruments mounted on the spacecraft’s instrument deck is REXIS, the REgolith X-ray Imaging Spectrometer. REXIS is unique among the instrument suite because it was designed and built by undergraduate and graduate students at MIT and Harvard University. It is an X-ray spectrometer that will study the X-rays fluoresced by Bennu in response to the impinging solar wind. By measuring the energies of the emerging X-rays REXIS measurements will reveal the elemental composition of the asteroid and map elemental abundance variability across the asteroid’s surface. REXIS is the first application of X-ray coded-aperture imaging to planetary surface mapping, and will be a pathfinder toward future planetary exploration.
IMAGING THE ASTEROID

REXIS has two primary science objectives: categorize Bennu’s elemental abundance properties within the range of known meteorite groups, and map the spatial distribution of elemental abundances on the surface of the asteroid. These objectives complement other OSIRIS-REx instruments that will deliver mineralogical maps of Bennu through visible and near-infrared spectroscopy. REXIS detects the elements in Bennu’s regolith by studying its X-ray fluorescence. Solar X-ray flux impinges on the asteroid, excites the atoms in the regolith and causes them to emit their own X-rays. The energies of the emitted X-rays depend on the elements present. REXIS is designed to detect the fluoresced X-rays. Over the soft X-ray energy range of 0.5 to 7 kiloelectronvolts (keV), REXIS seeks to identify iron, aluminum, magnesium, silicon, and sulfur. To map the spatial distribution of the elements, REXIS uses a coded aperture mask (having a 50% open fraction). The openings within the mask act in a manner similar to a pinhole camera, where the many pinholes increase the overall X-ray throughput. The shadow pattern projected by the mask on the detectors, knowledge of the mask pattern, and the spacecraft’s pointing history are used to construct a map of the X-rays emitted from the asteroid. Repeated imaging of Bennu’s surface over the full range of longitudes allows for co-adding the mapping images for increased spatial resolution and higher signal-to-noise ratio elemental abundance measurements. REXIS has the anticipated capability to reveal a localized 4X enhancement of iron in the regolith with 50-meter spatial resolution.

In order for REXIS to meet these science goals, an accounting must be made for the variability of both the overall solar flux and its energy distribution. The total flux and spectral energy distribution during solar flares changes over timescales as short as a few minutes. Thus, REXIS consists of two components, a main spectrometer with a coded aperture mask and a separate Solar X-ray Monitor (SXM). The REXIS spectrometer is about the size of a shoebox and contains four charge-coupled devices developed and fabricated by MIT Lincoln Laboratory arranged in a 2x2 array. The spectrometer includes an electronics box with three custom circuit boards that interface with the OSIRIS-REx spacecraft and drive the CCDs. There is a one-time deployable cover that sits over the coded-aperture mask and protects the CCDs from radiation damage during the
cruise to Bennu. The spectrometer CCDs must be operated at cold temperatures (-60 °C) and are cooled passively using thermal isolation layers and a large radiator. The SXM is a much smaller instrument that is mounted in a separate place on the spacecraft and consists mainly of a silicon drift diode detector package made by Amptek Inc. During science observations the spectrometer aperture points toward the asteroid and the SXM points toward the sun to obtain knowledge of the solar flux arriving at the asteroid. The spectrometer and SXM are connected via a power and data harness that runs along the spacecraft deck.
A COLLABORATIVE STUDENT PROJECT

REXIS began in 2010 as a proposal effort led by Professor Richard Binzel of MIT’s Earth Atmosphere and Planetary Sciences Department, Professor David Miller of AeroAstro’s Space Systems Laboratory, and Professor Jonathan Grindlay from Harvard College Observatory. MIT SSL graduate student George Sondecker (SM ’11) was the student lead in the proposal. REXIS was among four proposed student collaboration projects chosen by the OSIRIS-REx project for its mission proposal to NASA in October 2010. In the summer of 2011, NASA selected OSIRIS-REx as a New Frontiers mission, and the REXIS project was underway.

REXIS development began as a project in the AeroAstro senior capstone design classes 16.83 and 16.31. The classes were led by this author, a research engineer in the Space Systems Lab; and Professor Sara Seager of MIT’s Earth, Air, and Planetary Sciences Department. A team of about 10 undergraduate students developed the instrument requirements and the preliminary design with the support of graduate student mentors, MIT faculty, and staff. The classes participated in two reviews: the System Requirements Review in January 2012 and the System Definition Review in April 2012. Despite its status as a student collaboration experiment that is non-critical to the success of the mission, the OSIRIS-REx project team put the REXIS students through the same rigor of review as for all the other mission-critical instruments.

At the conclusion of the capstone class the REXIS project was transitioned to a team of graduate students with support by undergraduates through the UROP program. Science support was provided by Binzel, as principal investigator and instrument scientist, and Harvard College Observatory researchers Branden Allen and Jaesub Hong. MIT Kavli Institute and Lincoln Laboratory supported the REXIS students with expertise in the area of CCD technology, implementation and handling. The Space Systems Laboratory provided engineering and design guidance along with
Aurora Flight Sciences. The students also worked closely with mentors at NASA Goddard Space Flight Center (the managing center for OSIRIS-REx) and spacecraft contractor Lockheed Martin.

The project implemented a “function, fit, fly” philosophy for the instrument development. First a series of Engineering Test Units (ETU) were developed to test the design concepts. Many of the ETUs were developed and tested by the capstone class and included a thermal system ETU, a deployable cover ETU, and electronic boards that tested various instrument functions. The ETU period lasted through the Preliminary Design Review in January 2013 and through that academic year. Next, Engineering Models (EM) were built that tested function at a higher level of assembly and tested the fit of the instrument within mass, power, and volume constraints. There were two separate Engineering Models: a structural EM that validated the thermal system and served as a dry run for the fabrication of custom parts and mechanical integration, and an electrical EM that tested the circuit board designs and early software. EM development and test continued up to and through the Critical Design Review in February 2014. Finally, the flight hardware build began in late 2014 with the delivery of the REXIS flight CCDs from Lincoln Laboratory. Integration and test of the flight unit took place during 2015. The instrument pre-environmental review and pre-ship reviews were held in June and September 2015, respectively.

OVERCOMING THE CHALLENGES

The REXIS program faced a number of challenges throughout the four years leading up to the successful integration with the spacecraft. The engineering challenges faced during the instrument development included the design of a passive thermal system that could reliably keep the CCDs below their operational temperature of -60°C, design of a one-time deployable cover to protect the CCDs from radiation during the voyage to Bennu, and the design of radiation tolerant avionics. Although REXIS is a student experiment and, as such, is risk-tolerant with respect to its own performance, the instrument needed to be suitable for integration with a much less risk-tolerant NASA spacecraft. Therefore, all spacecraft interfaces needed to be rigorously tested to ensure that
REXIS could do no harm to the host spacecraft upon integration and during flight. Since OSIRIS-REx is returning a sample of the Bennu regolith to Earth, REXIS had to be constructed, integrated, and tested under tightly controlled environmental conditions to ensure that the instrument does not threaten the pristine nature of the asteroid sample by contaminates brought from Earth. Along the way, the REXIS team encountered many of the pitfalls experienced by nearly all flight hardware teams including late design changes necessary for performance, parts lost to a shipping
accident, a contamination event in a thermal vacuum chamber, vibration test anomalies, damage due to handling during inspections, late-stage instrument repair, and regression testing. Yet, the student team persevered and the REXIS flight instrument was delivered to Lockheed Martin and installed on the OSIRIS-REx spacecraft in December 2015.

The real success of the REXIS story is that of the students who made this instrument possible. Over the course of the program approximately 60 students contributed to the instrument development, build, and delivery. The core REXIS team comprised 16 graduate students spanning the four-year program. Most students were from AeroAstro, but the team also included students from Mechanical Engineering and Electrical Engineering and Computer Science as well as Earth, Atmospheric, and Planetary Sciences. More than 40 undergraduates supported the team through the AeroAstro capstone class and MIT’s Undergraduate Research Opportunities Program. One student, Mark Chodas began as a senior in the capstone class and has continued as a graduate student on REXIS. At the time of this writing he is in his PhD program and will have seen REXIS through as system engineer from requirements development to launch, an outstanding experience and accomplishment for an early-career engineer. Former REXIS students now work at the Jet Propulsion Laboratory, Oracle, SpaceX, Blue Origin, and Lincoln Laboratory. Others are training to be fighter pilots for the Air Force or are stationed at the National Reconnaissance Office and the Los Angeles Air Force Base. REXIS will carry each of their contributions into interplanetary space, and in turn, each student carries the REXIS experience into future careers.

REBECCA MASTERSON (Mechanical Engineering ‘97, SM ‘99, PhD ‘04) is a research engineer in the AeroAstro Space Systems Lab. She provided engineering guidance for the REXIS student team and overall instrument management. Her research interests include dynamics and controls, integrated modeling, control structure interactions, systems engineering, and engineering management. She may be reached at becki@mit.edu.
nuTonomy, a company co-founded by AeroAstro Professor Emilio Frazzoli (far right), is focusing on Level 4 "full autonomy," requiring the system to cope safely with any situation the vehicle encounters. (Doug Parker photograph)
Indeed, as the technology is maturing rapidly, the automotive industry is rethinking itself to face the potential impacts on its established business models, urban planners and transportation experts are working to assess the societal effects, and the authorities are developing new regulations and policies governing the operations of self-driving vehicles.

However, as autonomously-driven miles accumulate, accidents and crashes in which the automation is at least partly to blame have started to be reported. The first reported fatal crash of a vehicle controlled by an automated system (not a fully autonomous vehicle) occurred on May 7, 2016: a Tesla model S, under the control of its Autopilot, collided with a tractor-trailer crossing its path. Sadly, the driver later succumbed to the injuries caused by the collision. Initial statements by Tesla attributed the incident to the missed visual detection of the white trailer against a brightly lit sky, combined with a radar signature that was consistent with overhead signage. An investigation by NHTSA and NTSB is under way, and we will learn more about the accident in the coming months.

This tragic event naturally spurs a deeper reflection on the technology, its readiness, and its consequences on society. A thoughtful answer to the question of whether the technology for self-driving cars is ready for real-world deployment at scale requires a careful analysis of the use cases, the benefits, and the risks associated with it.
JUST WHAT IS “SELF-DRIVING”?

There is some confusion about what one can expect from “self-driving cars.” The term often refers to an idealized vision combining today’s cars with infallible computers able to drive them, surpassing the capability of human drivers. The reality is far from it. In fact, many different conceptual and engineering approaches are being pursued by several players, revealing profound differences in what a “self-driving car” would be and its potential social and economic impact.

On one hand, there is the approach that is typically favored by the automotive industry, which is based on a sequence of incremental advances in the technology, and their implementation on production vehicles made available for purchase to the general public. Indeed, we already have many systems on board today’s cars that provide a form of automation without us noticing: Examples include cruise control, ABS, and electronic stability control. NHTSA classifies this as “Level 1” automation. We have come to accept these as reliable safety-enhancing features on our cars.

Level 2 automation involves at least two primary control functions (e.g., steering and speed control) to relieve drivers’ workload, while requiring them to be fully engaged at all times. The manufacturer classifies the Tesla Autopilot as Level 2 automation.

In Level 3 automation systems, a driver could cede complete control of the vehicle, while being expected to intervene occasionally, upon request, and within a sufficiently comfortable transition time.

Level 4 automation, or “full autonomy,” does not require or expect driver intervention, besides choosing a destination, route, or other navigational preferences. In fact, at this level of automation, no human driver or passenger is required to be on board.

(Right) The National Highway Traffic Administration categorizes five levels of vehicle automation; from no automation, to full self-driving capability.
The National Highway Transportation Administration’s Five Levels of Vehicle Automation

**LEVEL ZERO**
No Automation. The driver is in complete and sole control of the primary vehicle controls — brake, steering, throttle, and motive power — at all times.

**LEVEL ONE**
Function-specific Automation. Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.

**LEVEL TWO**
Combined Function Automation. This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.

**LEVEL THREE**
Limited Self-Driving Automation. Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time.

**LEVEL FOUR**
Full Self-Driving Automation. The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.
While this may seem a logical progression, the path is fraught with peril. In particular, the boundaries between Levels 2, 3, and 4 are at least fuzzy, and following this path to Level 4 presents many challenges that are extremely hard to face when one takes into consideration not only the technology, but also the fundamental characteristics of human nature. Indeed, any automation system that, by design, relies on a human supervisor’s intervention in certain situations implicitly assumes that the human supervisor is part of the system. Unfortunately, no matter how well the automation part is designed, human nature cannot be designed to specifications, especially when one needs to address the general public versus highly trained professionals.

No matter how well the automation part is designed, human nature cannot be designed to specifications.

For example, even though the Tesla Autopilot is technically described as Level 2 automation, requiring constant attention by the driver, its undeniable sophistication, as well as the hype surrounding the technology, make it easy to erroneously think of it as Level 3, allowing the driver to cede control completely. While we await the results of the NHTSA investigation, it seems likely that one of the causes of the Tesla fatal accident was the confusion between what the Autopilot could provide (Level 2), and what the driver expected (Level 3). Furthermore, even the most disciplined driver would not be able to constantly remain alert and maintain situational awareness for more than a few minutes at a time when the car is under control of an automated system. This is a well-known and hard-learned fact in the aerospace community: many airliner crashes, killing thousands of people, have been traced back to issues arising at the interface between humans and automation, such as mode confusion, loss of situational awareness, and reduced ability to handle emergency situations. Paradoxically, the more sophisticated an automation system is, the more it can lead a human pilot to lose the ability to intervene effectively. It is shocking that at least part of the automotive industry seems to be unaware of this body of knowledge.
FOCUSING ON FULL AUTONOMY

How to avoid these problems? An arguably better option is to skip Levels 2 and 3 altogether, and focus directly on Level 4 automation. This is a path that is being followed by other players in the field, such as Google, and nuTonomy, the company co-founded by the author, based on several years of work done with colleagues and students at MIT AeroAstro. Instead of relying on a human taking over when necessary, Level 4 “full autonomy” automation requires the system to cope safely with any situation it encounters. Human override may be allowed (e.g., during testing and development), but is not necessary for safe operations. While apparently harder than Level 2 or Level 3, developing Level 4 automation is a problem that is, in fact, easier to define, understand, and eventually solve. In a Level 4 automation system, the car would remain within the boundaries of an operational envelope it defines, and within which it knows it can operate safely.

One may wonder whether such an approach would be too ambitious a step, and whether the incremental path through Levels 2 and 3 would be more reasonable. The answer is that even Level 4 automation can be introduced incrementally, in terms of, for example, complexity of the scenarios in which it operates, speed levels, fleet size, and other criteria. Many Level 4 autonomous vehicles are being deployed today, operating at low speed in closed or relatively controlled environments. Examples include the Ultra system shuttling passengers between terminals at Heathrow, the Navya ARMA shuttle on trial on the streets of Sion, Switzerland, and the Easymile EZ10 on trial in the Gardens by the Bay in Singapore and other locations. It is expected that first deployments of Level 4 systems will be in geographically defined locales (e.g., specific routes in a defined area of a city) for applications such as (local) mobility on demand, or first- and last-mile connectivity to transportation hubs. The technology to offer such services in a safe way is nearing maturity rapidly: nuTonomy is planning its initial commercial offering for 2018 in Singapore.

Level 4 automation can be introduced incrementally, in terms of complexity of operation scenarios, speed levels, fleet size, and other criteria.
So which one is the right approach? We may have the answer in front of us in the form of the well-established process that is used to teach humans how to drive and grant them a driving license. Upon passing a written test proving basic theoretical knowledge of the rules of the road, applicants are provided with a learner’s permit, allowing them to drive under certain conditions, usually involving an experienced driver sitting next to them, and restrictions on the time of day, the types of roads they are allowed to drive on, and the kind of vehicles they may operate. This is typically augmented by self- or instructor-induced limitations, by which new drivers typically acquire basic skills in secluded locations such as parking lots or back streets, gradually moving on to more challenging scenarios. In each of these situations the novice driver is expected to be fully responsible for driving the car; rather than performing only one or two functions, or relying by design on the instructors to avoid an obstacle, keep the speed limit, or stop for a traffic light. Warnings or overrides (e.g., the experienced driver-passenger seizing the controls) may happen, but these are perceived as driver failures rather than a means to mitigate difficult situations.

So, why not follow a similar process for fully autonomous cars? Let Level 4 automation systems have complete authority on the vehicle, but restrict the conditions under which they are able to operate, possibly mandating the presence of a professional safety driver onboard, and appropriate workload conditions for the safety driver. Once the vehicle can demonstrate increasing level of competency (possibly by a combination of real and simulated driving records, using naturalistic or synthetic data), to the satisfaction of the relevant authorities, reduce the restrictions until the point at which the automation is deemed safe to operate at the desired level.
This is a future that is within reach, with a clear path towards safety verification and validation, and which has the potential to resolve many of the current issues with mobility, especially in urban areas, by reducing the demand for parking, traffic congestion, as well as increasing the availability and affordability of transportation options.

EMILIO FRAZZOLI is a professor in the MIT Aeronautics and Astronautics Department and the CTO of nuTonomy Inc., a startup developing autonomous mobility-on-demand systems, which he co-founded with Karl Iagnemma in 2013. His current research interests focus primarily on autonomous vehicles, mobile robotics, and transportation systems. Emilio Frazzoli may be reached at frazzoli@mit.edu.
Enterprise, an “executive” system developed by MIT’s MERS group, will provide broad autonomous capabilities for Woods Hole Oceanographic Institute’s Nereid Under Ice vehicle, pictured here on a test deployment, as it retrieves samples from a Mediterranean subsea volcano. This research is a precursor to anticipated missions (inset) that will explore beneath the oceans of Europa and Titan.

(Ken Kostel photograph, ©Woods Hole Oceanographic Institution)
Looking further into the future, the “holy grail” of space missions is an explorer that looks for evidence of life deep under the ice of Jupiter’s moon Europa.

Over the last decade NASA has had great success at exploring the surface of Mars using sophisticated hardware and a relatively simple operations paradigm. The rovers carry out a linear sequence of low-level tasks that are assigned to them by an operations team comprising human scientists and drivers. The rovers are protected from failure through a set of fault detection rules that largely halt the mission until operators can intervene.

During each operations cycle, the operation team devotes most of its time to the tedious task of writing down these sequences, and testing that they are correct. The time required to write these sequences seriously detracts from the operator’s ability to focus on strategy and science. In addition, when sequence errors creep into rover operation, the mission is often aborted, and science is lost for the day, thus degrading science return provided by this expensive instrument.

A similar paradigm is applied to most planetary and Earth orbiting missions, and back on Earth for underwater exploration, for manufacturing robots, and for some aerial drone missions. In each case, the process is time consuming and error prone. It distracts the operators from thinking strategically, can be brittle to failure, and can limit the range of the technology’s application.

Goal-directed risk-aware autonomous explorers

by Brian Charles Williams

Planetary scientists have set their appetite for an ambitious slate of missions that they’d like to see over the next decade, including a Venus lander, a tour of the Trojan asteroids, the Mars Sample Return, and even an interstellar mission.
VEHICLES ADAPT TO ACHIEVE GOALS

A new operations paradigm is needed to perform ambitious tasks, in space and air and on sea and land, using recent advances in unmanned vehicle hardware. This paradigm should allow the operator to guide vehicles strategically, should enable vehicles to dynamically adapt to their environment without the need for human intervention, and should offer provable, probabilistic guarantees on correctness. The Model-based Embedded and Robotic Systems group (MERS), which I lead, is enabling this paradigm through the creation of an execution architecture for controlling autonomous systems that are goal-directed and risk-aware, and by validating this executive, called Enterprise, on space, undersea, and related systems, both in the lab and in the field. Scientists and engineers guide the Enterprise executive by specifying science goals and operations requirements. Enterprise then uses a range of reasoning methods, including science data analysis, task and motion planning, diagnosis and repair to robustly achieve these goals and requirements.

In support of these future space missions, the Keck Institute of Space Sciences commissioned a two-year study by the Jet Propulsion Lab (Mitch Ingham, John Day, Len Reder), led by Caltech (Richard Murray) and MIT (Brian Williams), to analyze the top 10 planetary missions proposed by the most recent decadal plan for space sciences, and to determine the requirements for flight software and operations architectures that will be needed to support these missions.

Due to the corrosive environment, the lander will likely need to diagnose and repair itself to remain operational until the end of its mission.

In the case of the Venus lander mission, the lander will have roughly a six-hour window to drill, collect, and analyze samples, and then upload data, while acting in a highly corrosive environment. Given the mission’s short time window, the lander will need to act without human intervention. Due to the corrosive environment, the lander will likely need to diagnose and repair itself to remain operational until the end of its mission. If the lander is going to use in situ data to help decide where to collect samples, it will need to make these decisions autonomously.
The Trojan Asteroid Tour is an example of a decade-long mission in which the space vehicle becomes quite active during an encounter, and then goes into hibernation during long cruise phases between encounters. Operation teams will support each encounter, but due to operations cost, the vehicle will need to be largely autonomous during the cruises. Because of the long duration between encounters, the operations team will likely change between each encounter, without overlapping the preceding team. This presents a significant opportunity for handoff errors. To avoid these errors, the space vehicle will need to be its own caretaker, and source of “corporate memory.”

The Interstellar mission accentuates issues highlighted by the Venus and Trojan asteroid missions. The science opportunities and operation challenges introduced by this type of mission are particularly hard to anticipate, plan for, and encode into predefined command sequences. The same holds for a Europa under-ice mission, which has the added challenge of operating within a fluid environment, thus combining challenges found in autonomous space and autonomous air missions.

The study’s final report included two takeaways. First, these missions should be commanded in terms of mission goals, rather than low-level command sequences. These goals should include the goals and priorities set by the scientists, and the operational safety constraints identified by the engineers. The space systems execution architecture, split between onboard and on the ground, should then use decision-making algorithms to plan what observations to make and which samples to collect in order to achieve these science goals; it should then decide what command sequences should be issued to achieve these science plans according to engineering operational constraints, and should perform self-diagnose and repair, in order to extend mission life.
Second, these missions operate in an uncertain environment in which the risk of failure is significant. Engineers and scientists strive to carefully evaluate these risks before sending a command sequence to a vehicle for execution. Since our approach involves automatically generating command sequences without frequent human intervention, human operators should specify to the executive what types and levels of risk are acceptable, and the executive should use models of uncertainty to generate command sequences that operate within these risk bounds, and should engage human operators for assistance, when these risks become unacceptable.

**ENTERPRISE EXECUTIVE — GOAL DIRECTED, RISK AWARE**

Enterprise, developed by the MIT MERS group, is one instance of a goal-directed, risk-aware executive, and takes inspiration from the different roles performed by crewmembers on the bridge of the fictional starship *Enterprise* of the Star Trek franchise. One component of the system acts as a “captain,” making higher-level decisions to plan out the overall mission, while taking input from a second component, the “science officer,” on where and when to explore. Another component functions as a “navigator,” planning out a route to meet mission goals. A fourth component works as a “doctor,” or “engineer,” diagnosing and repairing problems autonomously. A final component acts as a “communications officer” to communicate plans, explain issues, and propose alternatives back to the scientists and operators.

For example, for a Mars rover mission, human scientists could specify their science goals and priorities for a particular area being traversed. Enterprise’s science officer could identify candidate locations to observe and sample, along with estimates on the information they would provide. The captain would then come up with a plan for operating the rover for the day, while selecting locations for making high-valued observations, while consulting the navigator on how best to safely traverse between these locations, and while ensuring that the rover battery is not depleted. When executing the mission, the engineer would continuously monitor the health of the rover hardware, and would implement repairs if, for example, a science instrument or communication subsystem failed.
Enterprise is closely related to a system called Remote Agent, which I developed with NASA colleagues following the loss of Mars Observer, a spacecraft that, days before its 1993 scheduled insertion into Mars’ orbit, permanently lost contact with NASA. While skilled operation teams were available to diagnose and repair Mars Observer, they were defeated by the lack of communication. Subsequently, NASA realized that it needed systems on board a spacecraft that could reason at a cognitive level, similar to its engineers. In May 1999, Remote Agent successfully controlled the NASA Deep Space One probe, two weeks prior to its asteroid encounter, and demonstrated the ability to diagnose, repair, and re-plan its mission.

The types of goal-directed methods demonstrated on Deep Space One have subsequently supported a range of missions, including Earth Observer One, the Spirit and Opportunity rovers and the recent Rosetta mission. Meanwhile, advances in the research community have made goal-directed systems easier to use, faster, and more robust. Enterprise leverages many of these advances.

Returning to the second aforementioned finding in the KISS report, a significant barrier to adopting goal-directed execution widely is mission risk. The correctness of the actions generated by a goal-directed executive depends upon the correctness of the model used to generate them. Unless the executive can reason about model and environment uncertainty, and prove that mission risks are not excessive, deployment of goal-directed execution will be limited.

Enterprise embodies the concept of a goal-directed executive that is risk aware. The operator specifies to Enterprise acceptable risk levels for different types of failures, such as missing a science observation, failing to reach an end-of-day rendezvous point within a specified time, depleting the battery below a specified level, or moving into an untrafficable area with soil slippage. The captain asks the navigator for routes between points of observation that avoid untrafficable areas and avoids battery depletion within the specified risk levels. The captain then selects an overall mission plan that maximizes science, while ensuring that the end-of-day rendezvous is reached on time, again to the specified risk level. If the captain cannot succeed, the communicator explains to the operations team why their goals are too risky, and proposes ways to relax the mission goals, so that risk becomes acceptable.
Validating a risk-aware executive on a space mission is difficult. Conventional wisdom is that a prerequisite for flying a new technology in space is that the technology has already been flown in space. Deep space missions are simply too costly to be effective at maturing these technologies. Simulations, while a stepping-stone, can only go so far.
However, deep-sea missions offer an excellent environment. Like space missions, deep-sea missions are often science driven, have severe communication constraints, and operate within a highly uncertain environment. The cost of unmanned deep-sea vehicles, however, are priced at the level of hundreds of thousands to millions of dollars, rather than hundreds of millions, are easier to deploy, and are easier to retrieve upon failure.

To cross the technology validation gap, a team comprising MIT, Caltech, JPL, and the Woods Hole Oceanographic Institution (WHOI) is conducting a two-year KISS-funded study to demonstrate risk-aware execution (MIT, JPL) combined with correctness-by-construction controller synthesis (Caltech), applied to a simulated rover and a fielded deep-sea mission.

In March 2015, the team tested goal-directed execution using Enterprise during a research cruise off the northwest coast of Australia, supported by Schmidt Ocean Institute. Over three weeks, the MIT MERS team, along with groups from WHOI, the Australian Center for Field Robotics, the University of Rhode Island, and elsewhere, tested several classes of AUVs, and their ability to work cooperatively to map the ocean environment.

Enterprise was tested on an autonomous underwater glider, in collaboration with Rich Camilli at WHOI, and demonstrated that the glider could operate safely among a number of other autonomous vehicles, while receiving high-level goals. The glider, guided by Enterprise, was able to adapt its mission plan to avoid getting in the way of other vehicles, while still achieving its most important scientific objectives. If another vehicle was taking longer than expected to explore a particular area, Enterprise would help the glider reshuffle its priorities, and, for example, choose to stay in its current location longer, in order to avoid potential collisions.

The team will soon test Enterprise’s risk-aware capabilities on a deep-sea glider off the coast of Santa Barbara, California, and the MIT-WHOI team is working with Exxon to extend risk-aware execution to the coordination of teams of exploration vehicles.
UNDER THE ICE OF JUPITER’S MOON

The team’s most ambitious plan is to use Enterprise to help conduct a field demonstration of a Europa analog mission. Exploration of the oceans of Europa and Titan are the next big challenges in extra-planetary exploration. Such missions would vastly increase our knowledge of the solar system and, on Europa in particular, may result in the discovery of life. To conduct these missions, the space systems will need to demonstrate high levels of self-reliance and risk-awareness.

To prepare for this challenge, NASA awarded funding to a team of researchers from WHOI, MIT MERS, University of Michigan, and ACFR to conduct an Earth analog of these missions in the Kolumbo volcano caldera, the most active subsea volcano in the Mediterranean Basin. This underwater caldera is a complex, hazardous environment that serves as a suitable analog for autonomous risk-aware exploration of other planetary bodies containing liquid water. As part of this demonstration, the team will explore for life forms in and around carbon dioxide accumulating subsea pools, providing a unique opportunity to characterize life that flourishes in extreme carbon dioxide environments. Enterprise will be used to autonomously guide a long-range underwater glider that maps out the caldera to identify sites of scientific interest, and to guide WHOI’s Nereid Under Ice vehicle and its manipulator, to retrieve samples from those sites.

Exploration is just one area in which goal-directed execution is injecting a paradigm shift. On Earth, the MERS group is using Enterprise to develop a new generation of cognitive systems for social good. Examples include:
» with Toyota, MERS is developing assistants that help drivers and autonomous cars avoid risky situations

» with Woods Hole and Exxon, MERS is developing networked mobile observing systems for monitoring the ocean environment

» with Boeing and Mitsubishi, MERS is developing robots that work safely and fluidly with human teammates

» with Tata, MERS is developing sustainable micro-grids for villages in India that previously had no source of power

» with DARPA, MERS is developing an internet that adapts in order to avoid cyber-attack

In each case, Enterprise enables these cognitive systems to increase autonomy within acceptable risk.

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Professor Steven Hall’s expertise in optimal control theory helps pilot Michael Goulian select the best speeds and flight paths as he maneuvers his aircraft around race courses, as Goulian is doing here during training for the 2016 Red Bull Air Race World in Chiba, Japan. (Red Bull photograph)
Applying optimal control theory to air racing

by Steven R. Hall

During the last two years, I’ve had the opportunity to apply knowledge of aerospace engineering and, in particular, optimal control theory, as a member of a Red Bull Air Race team. The race series is sanctioned by the Fédération Aéronautique Internationale and usually comprises eight events per season run at locations throughout the world.

My involvement with the air race series began in August 2014 after I heard that race pilot Michael Goulian was looking for technical help to improve. I realized that I could use my knowledge of aerospace engineering, especially optimal control theory, to help him fly the airplane faster. After meeting with Michael, I became a member of the team.

The air race teams are small, typically with only three to five team members, including the pilot. My team, Team 99, has four members: team leader and pilot Goulian, technician Warren Cilliers, team coordinator Pablo Branco, and me. I serve as the team tactician.

THE RACE

Each race is run in heats, with a single plane at a time on the track. The race is flown over a course defined by a number of gates, typically covering about 5 km in a closed circuit, and takes about one minute to complete. The gates are defined by 25 m tall inflatable pylons, which are designed to safely tear if hit by an airplane. There are two types of gate. An air gate is a pair of pylons, set 13 m apart, that pilots must fly through in a level attitude. There are also single pylon gates, often set up in groups of three to form a chicane or slalom. Pilots must past by single pylon gates at the appropriate height, and not be descending or climbing, but need not have wings level.
Much like a formula car race, the rules specify what aircraft can be flown. Most pilots fly a modified Zivko Edge 540 (Version 2 or 3), manufactured by Zivko Aeronautics in Oklahoma. The Edge 540 is a 300 hp single place aerobatic aircraft. All aircraft use the same model engine and propeller, and no modifications may be made to them. Some modifications may be made to the aircraft aerodynamics, induction, and cooling systems.

Unlike most other air races, such as the Reno race, the Red Bull races are designed to be aerobatic, with rapid maneuvering and acceleration levels up to 10 g. For a pilot, it’s not obvious how to minimize the time it takes to complete a run through such a track. Turning as tightly as possible near each gate can reduce the total distance traveled, but a tight turn requires a high load factor (lift divided by weight), which in turn produces greater drag and thus slows the airplane. Larger radius turns produce less drag, and so don’t slow the aircraft, but increase the distance traveled. The trick is to find the right racing line that best balances the tradeoff between the distance flown and speed of the aircraft.

**OPTIMAL CONTROL THEORY**

The problem of how to fly an aircraft around a racetrack as fast as possible is an example of an optimal control problem. The history of optimal control theory stretches back more than 300 years to the solution of the brachistochrone problem (to find the shape of the curve down which a bead sliding from rest and accelerated by gravity will slip from one point to another in the least time) but interest in optimal control theory in engineering, especially aerospace engineering, ballooned in the 1960s, fueled in part by the Cold War and the space race, and enabled by the advent of modern digital computing.

To formulate an optimal control problem, one needs three things: a model of the dynamics of the system of interest, the performance objective to be minimized, and any constraints on the problem. For the air race problem, we use a simplified dynamic model of the aircraft flight mechanics that captures the performance of the airplane and, of course, the performance objective is to minimize the time around the track.
There are a number of constraints on the problem that come from the physics of flight, but also from the rules of the race. By rule, the aircraft accelerations cannot exceed 10 g. (1 g is the acceleration due to gravity.) In addition, the aircraft will stall if the coefficient of lift exceeds a threshold, and so the available lift depends on the speed of the aircraft.

Aircraft must past through the air gates (double pylons) in a level attitude, and within a narrow altitude range. The aircraft ground speed cannot exceed 200 kt at the start gate. It’s often beneficial to cross through an air gate at a heading different than the heading of the air gate, but the more oblique the crossing, the less space there is to fit through the gate. So there’s a limit to the gate crossing angle. (The actual limit used depends on the risk the pilot is willing take that he will strike a pylon and incur a time penalty.) In addition, there are often safety lines to protect spectators that the aircraft may not cross, and which constrain the optimal path through the course.

The optimization itself is performed using the same techniques we teach in AeroAstro class 16.323, “Principles of Optimal Control.” Using custom software, the problem is transcribed, meaning that the continuous trajectory is represented by the aircraft state at many discrete points in time. This reduces the original infinite-dimensional problem into a nonlinear program (NLP), which has a finite (but very large!) number of variables and constraints. Typically, the resulting NLP will have thousands of variables and constraints. Solving the NLP numerically yields the optimal control solution.
Flying the optimal line can significantly improve racing times. Although it’s very hard to quantify, lap times flown using an optimal line are probably on the order of one to two seconds faster than flying a line found using experience and intuition alone. Most races are won by margins of 0.1–0.5 seconds, so having the right race tactics can be the difference between winning and placing in the middle of the pack.

**THE HUMAN ELEMENT**

Part of my job as race tactician is to translate the results of my optimization into a format that’s usable by the pilot. Before each race, I prepare a report for pilot Goulian, so that he knows the best line through the course, and what g-levels are required to use in each turn. Point-of-view, virtual-reality imagery is created ahead of time, giving the pilot a perspective of the track as seen from the airplane’s cockpit during a lap. He uses that information to memorize and visualize the racing line, so that he already knows the track before his first flight.

Much of the important work happens during race week. Because there are, at most, three training sessions, it’s important to learn as much as possible from the limited time available on the track. After each training session or race heat, we use data from onboard sensors as well as video footage to analyze the flight. The data is used to compare the line flown to the optimal line, to find where improvements can be made. During post-flight analysis we are able to overlay optimal and actual trajectories, allowing us to know exactly where lap-time was lost or gained and continually perfect the strategy, shaving tenths of a second on every outing.
As we work to refine the racing line, it’s important to concentrate on only the few changes that will have the greatest impact. Optimal control tools help me understand the impact of those changes, and so choose the issues to work on for race day.

Finally, it’s one thing to sit at a desk and calculate optimal trajectories, but it’s another thing altogether to fly aerobatic maneuvers close to the ground along a prescribed racing line. It’s a sport that requires tremendous skill and athleticism. Helping Michael perform at his best requires more than just telling him the optimal line — it requires understanding how he flies the plane, and helping him achieve his peak performance on race day.

**BENEFITS AT MIT**

The air race experience has offered tangible benefits for my work back at MIT. In terms of teaching, the air race optimization problem is one that I share with my students in the graduate optimal control theory subject, 16.323. The technical challenges of the air race optimal control problem have given me insights into optimal control algorithms that I can apply to my research.

Participating as a member of a Red Bull Air Race team has been a terrific adventure, taking me all over the world, and allowing me to apply optimal control theory in new and exciting ways.

**STEVEN R. HALL** is a Professor of Aeronautics and Aeronautics at MIT. His research interests are in control theory and applications of control theory to aerospace systems. He can be reached at srrhall@mit.edu.
Ed Obropta (right), shown with (from left) Forrest Meyen (AeroAstro SM ’13), Michael Klinker (AeroAstro ’14, SM ’16), and Nikhil Vadhavkar, is the CTO of a new unmanned aerial systems company. He says students see innovative startups as a means of testing their ideas faster than if they were working for more traditional corporate or government research organizations. (Len Rubenstein photograph)
The chief technology officer of a young unmanned aerial systems technology company adds that he and his colleagues “see opportunities to do things today.”

Alumna Natalya Brikner, (AeroAstro PhD ’15), CEO of a satellite technology venture, agrees. She sees “space opening up to more people as the aerospace industry becomes more private.”

The “final frontier” has opened up, indeed, as the public can now fly commercially-produced drones, access real-time satellite weather and navigation technologies, or even purchase tickets for a future Virgin Galactic suborbital flight. With such changes, MIT AeroAstro students and alumni are finding themselves confronted with a range of unprecedented opportunities.

During the past century, MIT’s aerospace innovators helped win the race to the moon, shaped the nation’s aviation industry, perfected technologies that keep the nation secure, and begun probing the deepest reaches of the universe. These days, thanks to advances in technology and manufacturing, the proliferation of aviation as a mode of passenger and cargo transport, and reductions in governments’ appetites for large-scale space programs like Apollo, AeroAstro innovators can start their own companies, create their own aviation designs, build their own rockets, and make an impact outside of government facilities and large aerospace firms.
Brikner and her business partner Louis Perna (AeroAstro ’09, SM’14), began Accion Systems in 2012. Their company is based on a technology they developed with AeroAstro Professor Paulo Lozano in AeroAstro’s Space Propulsion Laboratory—a compact, inexpensive, electric-based satellite thruster system. These tiny rocket motors will enable inexpensive microsatellites to accomplish work previously possible only with large, expensive satellites. As a result of this new technology, sophisticated space missions once exclusively the province of government and large aerospace firms are now within reach of entrepreneurs like Brikner.

The challenge is getting this new technology from the lab to the marketplace, says Brikner. “I exhausted almost every startup resource MIT has,” she says. Brikner credits Lozano for providing “an early taste of how the industry works,” she says. “He let me be student manager for a multimillion-dollar NASA space program, and I was invited to be speaker at conferences he couldn’t attend,” she recalls. “I got exposure and was connected to people I otherwise would never have met.”

With Lozano as technical advisor, Accion has raised millions of dollars for prototyping and testing its first commercial system.

Brikner also took advantage of MIT’s Venture Mentoring Service, which helped prepare her and the team that would eventually form Accion, for the process of commercializing their nascent, compact technology for small satellites. The group entered the MITooK business plan competition, one of the many nodes of the innovation ecosystem on campus, and found a second home to fuel their start up idea and satiate their need for caffeine.

“I basically camped out at the Martin Trust Center for MIT Entrepreneurship,’ she says, “because we had legal problems, and with mentors there, dug our company systematically out of holes.”

Today, with Lozano as technical advisor, Accion has raised millions of dollars for prototyping and testing its first commercial system, the matchbook sized MAX-1, and is targeting early 2016 for its first delivery to customers. Brikner notes with pride that six of Accion’s nine employees are from MIT. “We’re turning mechanical engineers and material scientists into rocket scientists,” she says.
AEROSTRO IN CONTEXT

A new-technology venture in aerospace, Accion is not an outlier. According to a Dec. 9, 2015 report outlining MIT’s global entrepreneurial impact, alumni from the Institute are estimated to have launched more than 30,000 active companies that employ roughly 4.6 million people. These activities have generated nearly $2 trillion in annual revenues. Not surprisingly, among those alumni are many, like Obropta and Brikner, who come from AeroAstro.

Report co-author Edward B. Roberts, the David Sarnoff Professor of Management of Technology at MIT Sloan, explains that AeroAstro has played an important part in the Institute’s impressive overall economic impact, equivalent to the 9th largest GDP in the world. In fact, the AeroAstro innovation story is one he knows well, and personally.

In the early 1960s, while he was a PhD candidate in economics, Roberts was charged with helping a young NASA justify its funding to Congress. With funding and administrative support from Charles Stark Draper, then head of the AeroAstro, Roberts surveyed the MIT Instrumentation Lab and discovered 39 spinoff companies based on technologies developed at the lab.

Natalya Brikner (AeroAstro, PhD ’15) cofounded Accion Systems to develop advanced electric satellite propulsion systems based on technologies originated in AeroAstro’s Space Propulsion Lab. (Accion photograph)
“Our report was totally comprehensive, looking at markets, initial ideas, employment, everything,” he says. Roberts went on to survey not just aeronautics, but other departments, revealing a wealth of commercial ventures flowing out of MIT research labs. Fifty years after Roberts’ initial studies, AeroAstro students are wondering when, not whether, to market their own creations.

Obropta sums it up this way: “Students are eager to get out and take risks on their own ideas.” While pursuing his graduate studies, Obropta also lead software development for Raptor Maps, a drone and sensor company that monitors food crops from seed, through growth, to harvest — and winner of the 2015 MIT100K Entrepreneurship Competition. Obropta met his business partners in the Man Vehicle Lab, where all were advisees of Dava Newman, professor of Astronautics and Engineering Systems and currently deputy administrator of NASA, who encouraged them to pursue commercialization of their idea. Since then Obropta and lab-mate, Nikhil Vadhavkar, added Michael Klinker (AeroAstro ’14, SM 16) to their team, and entered Y Combinator, one of the most prestigious start-up incubators in the world.

AeroAstro professor and entrepreneur Ed Crawley says that although capital costs of aerospace startups are high, the markets are substantial. (William Litant/MIT photograph)

Many AeroAstro students, while inspired by longer-term projects like traveling to Mars, are looking for more immediate ways to get hands-on experience. “They want to try things, fail, and learn, and it’s hard to do when projects have such long time horizons,” Obropta says. “They see entrepreneurship as a way to test ideas faster.”
AeroAstro Professor, and former department head, Edward Crawley, sympathizes. When he arrived as a student in 1972, eager “to be a space guy,” he figured he would have to be involved either with NASA, or a large aerospace company. “But eight years later, when I considered my career options, I didn’t find these alternatives inspiring.” Instead, he devoted himself to research, the fruits of which included a number of significant spinoff companies.

Barriers for entry into the aerospace business have been high for a reason, Crawley says. “No startup could land on the moon,” he notes. But while the capital costs of an aerospace startup are high, he says, the markets are bigger. Companies such as Orbital Sciences (now Orbital ATK), Aurora Flight Sciences, Virgin Galactic, SpaceX, and Blue Horizons, have all emerged relatively recently, often with MIT alumni in major roles. “You either have to have $100 million of your own money, or a clever way to get a launch customer — it’s like starting a railroad,” Crawley says.

The majority of Crawley’s own spinoffs, and those of many others, have involved technologies or expertise developed for such clients as NASA — but then applied to these emerging markets. It’s far easier “to solve problems of society on the surface,” Crawley says.

One AeroAstro entrepreneur is following a similar tactic. Alex Mozdzanowska (AeroAstro ’02, SM ’04), manages research at the Cambridge start-up, Hopper, a mobile app that helps travelers find the best prices for their airline flights using novel data analysis. I love being in a startup,” she says. “We innovate quickly, and throw out things that don’t work.”

In short, she’s employing everything she learned in AeroAstro, from policy and data manipulation to interdisciplinary collaboration, to a decidedly more earth-bound problem, but still flying high.

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Student projects: tiny rocket drones, hyper-speed transport, a composite rocket, and a lunar orbit competitor
Following two years of exhaustive development, in 2001 AeroAstro implemented a unique educational initiative called CDIO, for Conceive-Design-Implement-Operate. For the last 15 years, the CDIO Syllabus has guided the AeroAstro Department’s education programs and initiatives. Guided by the syllabus, students receive a thorough education in engineering fundamentals, but, henceforth, these would be interwoven with considerable hands-on projects, and exposure to a wide-range of topics and skills vital to 21st century engineering such as teamwork, ethics, and communications.

Indeed, hands-on projects are an integral part of our AeroAstro education, both within the confines of coursework, and generated by extra-curricular clubs, paid and for-credit research opportunities, and engineering competitions and challenges.

For this issue of AeroAstro, we approached students involved in four hands-on projects and asked them if they would share them with our readers. These projects are:

» Firefly — a 550 mph micro unmanned aerial vehicle

» Hyperloop — a high-speed transportation concept consisting of pods traveling close to the speed of sound through partially evacuated tubes

» Therion — a rocket that uses electric wind to reduce drag

» KitCube — a backpack-size spacecraft competing for a NASA launch to lunar orbit

This special section is testament to our students’ allegiance to an AeroAstro motto: “The sky is not our limit.”
The 550 mph Firefly

by Tony Tao

MIT Beaver Works is a collaboration between MIT and Lincoln Laboratory that gives students the opportunity to design, build, test, and deliver actual flight vehicles for external customers, notably the US Air Force and US Navy. This has proven a unique opportunity for the students to integrate their academic experience with real world engineering experience.

Between 2010 and 2012, the Beaver Works students were commissioned to develop a small expendable UAV to be deployed from a full-scale aircraft at 30,000 feet and autonomously fly a one-hour environmental monitoring mission. The preferred launch platform was a flare dispenser, which required the vehicle to fit into a 2-inch by 2.5-inch by 7-inch cartridge. The end result was a tiny folding aircraft christened “Locust.”
Jump ahead to 2016, and the BeaverWorks group is developing what is, in effect, a Locust on steroids: a high-speed, in-flight-deployable micro-UAV called Firefly.

Firefly is longer (around 16-inches long), but about the same width as Locust. And, like Locust, Firefly will also deploy from a mothership aircraft, unfold its wings, and fly autonomously. The main performance difference between the two vehicles is speed.

Whereas Locust was developed to maximize endurance using electrical propulsion and flies at approximately 60 mph, Firefly’s mission requires cruise speeds of around Mach 0.8, or about 550 mph at an altitude of around 20,000 feet. To generate sufficient thrust for such high flight speeds, a solid rocket propulsion system is used. Whereas other applications of small solid rockets boost a rocket to altitude quickly (and therefore expend its fuel in a few seconds), Firefly is designed to fly for several minutes. Firefly will offer its users the novel capability of deploying small, self-flying electronic payloads in mid-air, capable of filling a wide variety of missions. The speed, range, and autonomy of Firefly have never before been achieved in a vehicle this small.

To maximize the endurance of the vehicle, the team is developing a custom solid rocket propulsion system using a cocktail of various fuels, burn rate modifiers, and catalysts to tune the rocket motor for efficiency, ignition stability, and burn rate. To protect the vehicle chassis and onboard electronics from the heat generated by the rocket motor, ceramic-fiber-silicone composite liners are being developed and a ram-air intake cooling barrier is being designed.
To take up as little space as possible, Firefly is stowed folded, with its main wing pivoting 90 degrees, and its tails collapsing like switchblade knives. The folding mechanisms must allow the vehicle to deploy at supersonic speeds, but are about the size of a silver dollar (for the wing) and a gumdrop (for the tail).

To stabilize the vehicle in the high-speed launch environment, a shuttlecock system is designed. The shuttlecock has long folding fins for stability and carries the laser ignition system for the motor onboard Firefly. When oscillations from deployment have subsided and the motor is ignited, the shuttlecock splits, disengages from Firefly, and falls away, leaving Firefly in its low-drag cruise configuration. Indeed, the Firefly project breaks new ground in slow-burn propulsion systems, system configuration and packaging, thermal design, and folding mechanisms, all at micro scale.

The Beaver Works Firefly team is led by AeroAstro grad students Tony Tao and Matt Vernacchia and includes undergrads Zach Bierstedt, Sasha Galitsky, Charlie Garcia, Madeleine Jansson, Michael Trinh, and Juju Wang. Past team members were Andrew Adams, Brad Jokubaitis, and Jonathan Zdasiuk. The team conducts its research and development in the AeroAstro’s Gelb Laboratory, with chemical handling facilities and blast chamber in the Ronald McNair Building (Building 37).

**TONY TAO** is a graduate student in the AeroAstro Department and a leader of the Beaver Works Firefly Team. He may be reached at tonytao@mit.edu.
The Hyperloop is a concept for high-speed transportation that consists of pods traveling close to the speed of sound through partially evacuated tubes elevated above the ground. The dream is to be able to travel between cities like San Francisco and LA, or Boston and New York in half an hour, in an efficient, convenient, and environmentally friendly way. It has the potential to change how we think about transportation.

In June 2015, when SpaceX announced that it would sponsor a Hyperloop pod design competition, two graduate student members of AeroAstro’s Aerospace Computational Design Lab felt compelled to get involved. Joined by a grad student from the Gas Turbine Lab, the three started working on forming a team that could tackle the audacious and multidisciplinary challenge.
Meanwhile, a group of MIT Mechanical Engineering students had the same idea and was forming a team of its own. The two groups learned about each other and, after the inevitable AeroAstro and MechE rivalry subsided, they joined forces to make one large team to represent MIT—a decision that proved instrumental to the team’s success. Over the course of the year the team grew to approximately 30 students, with representation not only from AeroAstro and Mechanical Engineering, but also from Electrical Engineering and Computer Science, and the Sloan School of Management. The AeroAstro contingent comprises graduate students Philip Caplan, Rich Li, Max Opgenoord, Philippe Kirschen, and Derek Paxson. The first three are on the Aero/Structures team; the latter two on the Levitation team.

The competition has two phases: a design phase and a build phase. The former culminated in January 2016 at a design weekend at Texas A&M University in which our team showcased our design with a display booth and 20-minute presentation to judges, the public and other competing teams. Much to our surprise, we won best overall design!

Since then we’ve put the finishing touches on our design (including addressing some rules changes), prepared for manufacturing, and conducted testing.

**FIRST PROPOSED BY ROBERT H. GODDARD**

The rapid rise in popularity of the Hyperloop concept would lead one to believe that it is a completely new idea. However, as is the case with most modern engineering designs, it is really a re-combination and rebranding of concepts that have been around for more than a century. Every aspect of the pod outlined in SpaceX’s 2013 white paper, “Hyperloop Alpha,” from the high-speed air bearings, to the large compressor to alleviate choking, to the basic concept of high-speed evacuated tube transportation has been proposed in the past. As early as 1909, Robert H. Goddard, best known as creator of the first liquid-fueled rocket engine, proposed high-speed passenger-carrying pods traveling in an evacuated tube. Even more closely resembling the Hyperloop Alpha concept was a design proposed by Rensselaer Polytechnic Professor Joseph Foa as early as 1947 for a fan driven, air bearing suspended train travelling in a tube. Modern battery technology will allow for the system to be greener, replacing Foa’s fossil fuel burning gas turbines with an efficient electric compressor, but the basic concept remains the same. What Elon Musk has done for the technology
is bring it to the forefront of the public interest. Just as the Tesla roadster breathed new life into the largely stagnant electric car industry, and the inexpensive and reusable rockets of SpaceX forced established launch companies to reconsider their design philosophies, the Elon Musk stamp of approval has allowed evacuated tube transportation to quickly progress from a collection of disparate engineering concepts to a coherent segment of academic research and industrial innovation. With the creation of the MIT Hyperloop team, almost 200 other university teams, and two successful startups, the Hyperloop concept is rapidly transitioning from idea to reality.

AERODYNAMIC CHALLENGES AND ANALYSIS

The overall concept of the Hyperloop raises several interesting scientific challenges capable of endlessly tickling the curiosity of engineers. As a team, we needed to determine which of these challenges were relevant to the competition put forth by SpaceX. For example, the full-scale Hyperloop would need to overcome the so-called “Kantrowitz limit.” This limit is reached when the flow around the pod reaches the speed of sound. No additional air would be able to pass over the pod (a concept called “choking”) and the aerodynamic drag would increase dramatically as the pod continued to accumulate the air ahead of it. In other words, air would be trapped in front of the pod and, over time, it would be pushing an entire column of air in front of it, instead of floating through it. Some back-of-the-envelope calculations for the tube geometry and of our preliminary design revealed we were safe from the Kantrowitz limit for this competition.

On the topic of aerodynamic drag, we also needed to tweak our design over the course of the competition due to changes in the minimum tube pressure SpaceX could provide. Initially at 130 Pascals, we were confident that the aerodynamic drag was insignificant relative to the levitation drag induced by the magnetic skis. The change to a minimum tube pressure of 860 Pascals meant the flow regime over the pod would be a combination of both laminar and turbulent flow. As astute students of AeroAstro Professor Mark Drela’s course on viscous fluids, we turned to his software MTFLOW to model various axisymmetric profiles and determine which geometry would reduce the flow separation behind the pod and avoid excessive laminar separation bubbles, known to negatively impact drag. We also used MTFLOW to model the effects of “boundary layer tripping,” which essentially keeps the boundary layer attached to the pod as long as possible, thereby minimizing the drag induced by flow separation. This is the same concept behind the dimples you see...
in golf balls. Of course, you might think to extend the shell well beyond the back of the pod to reduce separation, but other interdisciplinary constraints, such as weight and center-of-gravity, as well as manufacturing considerations, pushed us away from such a concept. After we reached a final design, we used a commercial computational fluid dynamics solver, STARCCM+, to get a more accurate evaluation of the aerodynamic drag.

THE SHELL MANUFACTURING AND STRUCTURAL DESIGN CHALLENGE

Designing and building the aerodynamic shell posed many practical engineering challenges, and served as a good exercise in balancing mechanical performance, weight, manufacturability, production time, and costs—all key parameters similarly faced in the aerospace sector. As a result, this process applies a plethora of hands-on skill sets gained through the AeroAstro curriculum. For example, the structural design process and challenge faced for the shell was similar in many ways to that in aeronautical structures. The design configuration and materials selection was driven by key requirements in outer mold line geometry as previously defined in aerodynamic analyses, maximum aerodynamic loads, handling/transport loads, and weight budgets. Given their high mass-specific strengths and stiffness, carbon fiber reinforced plastics (CFRP) are increasingly being used in the aerospace industry (e.g., Boeing 787, Airbus A350) and were selected for our shell material to attain a lightweight, yet stiff shell structure. To predict the structural performance, micromechanical models were first used to determined carbon fiber/epoxy ply-level properties. Finite element analysis was performed and iterated to determine mechanical responses under maximum load case scenarios, such as ambient tube pressures, in the event of a qualifying atmospheric run at competition. Maximum deflections, stresses, and possible failure sites were calculated and compared with design allowables. Ultimately, a sandwich structure was chosen to increase the stiffness of the structure by placing high modulus carbon fiber reinforced plastic materials away from the neutral plane through the incorporation of a lightweight foam core. Areas that interfaced with fasteners and carried bolt-bearing loads were designed as monolithic laminates.
Additionally, manufacturability was a large driver in the final shell design. Given the two-month production target and the constraint on available autoclave systems, an out-of-autoclave process was utilized. To yield a high quality part with low void fractions and high mechanical properties, we employed a closed mold composite manufacturing technique called “vacuum assisted resin infusion.” In contrast to a typical wet layup, dry woven carbon fabrics were draped onto a female mold along with peel ply and porous distribution flow media before vacuum bagged. Vacuum was connected to one end of the mold, and a resin valve was slowly opened from the other end, thus cleanly introducing resin onto the carbon preform. Once the resin flow front had reached through the full length of the part, we closed off the resin source, and held the part under vacuum to cure at room temperatures. As we anticipate the shell to be exposed to the sun for extended durations on competition day, the glass transition temperature of the composite was elevated by post-curing the part. Designing and fabricating the composite mold also presented many key challenges in manufacturing. Due to cost and surface finishing constraints, a direct female medium density fiberboard (MDF) mold was designed and routed, thus requiring efficient tool path programming. After the MDF plies were assembled and glued, the tool surface had to be sealed, polished, and waxed to create a mirror surface, while also ensuring part release. In the end, we were successful in manufacturing two stiff, yet lightweight, CFRP shells within two months and they are now ready for competition.
THE LEVITATION CHALLENGE

The original concept outlined in Hyperloop Alpha utilized large low-pressure air bearings to provide a high-speed, low-friction system for supporting the pod. These bearings used both the relative motion between the pod and the tube, and pressurized air supplied by a multistage compressor to provide the airflow necessary to lift the pod. One of the major challenges of using such a fluid film bearing is the extremely small clearances that are required to keep flow requirements reasonable, maintain stability, and allow for reasonable hydrodynamic effects. Commercial air bearings typically operate at clearance of approximately 10 microns, whereas the bearings outlined in Hyperloop Alpha were designed for a much larger clearance of 1 mm. Initially, the team pursued a similar levitation strategy for the MIT pod. Using a combination of simple axisymmetric viscous flow models, 2-D CFD, and a multidisciplinary sizing tool, we determined a feasible maximum gap height for our pod. We considered using both compressed air cylinders and centrifugal compressors to supply the pressurized air to the bearings. The cubic dependence of mass flow rate on clearance caused tank volume or compressor power requirements to quickly reach impractical levels for clearances larger than 1-1.5 mm. Surface imperfections in an air bearing surface should not exceed approximately 1/4 of the total clearance, and this led to a maximum tolerable surface finish for the test track of approximately 250-400 microns. SpaceX released final tube specifications in November, which allowed for up to 1 mm step discontinuities between sections of the track on which the air bearings would ride. This forced us to move towards the passive eddy-current maglev system, which is currently used by the pod. This system allows for clearances an order of magnitude larger those of an air bearing while still maintaining low drag and feasibility at high speed.
ACKNOWLEDGEMENTS

None of our team’s successes would have been possible without the tremendous amount of support we have received over the course of this project. We have been guided by an incredible team of advisors, AeroAstro Professors Warren Hoburg and John Hansman, and alumnus Noel Zamot (AeroAstro SB ’86, Sloan ’16). They have attended all of our design reviews and given us valuable feedback at every step. As our team predominantly comprises graduate students, we are also each grateful to our research advisors for allowing us to spend time working on this project. Thanks to another of our team’s advisors, Mechanical Engineering Professor Doug Hart, several team members were able to receive class credit for this project, but it has nonetheless been a large time commitment. Finally, we are grateful to the entire MIT community that has been so supportive throughout this year. We have received donations from many alumni of the department as well offers of resources and expertise. This incredible sense of community has been a constant source of motivation for our team.

PHILIP CAPLAN, RICH LI, MAX OPGENOORD, PHILIPPE KIRSCHEN, and DEREK PAXSON are AeroAstro graduate students. Visit the MIT Hyperloop Team at mithyperloop.org.
KitCube a contender for a hitchhike to the moon

by Angela Crews

A team comprising MIT Aeronautics and Astronautics students, high school students from La Cañada Flintridge, Calif, and industry partners is one of the six remaining contenders for three possible launch slots to deep space or lunar orbit in NASA’s CubeQuest Challenge. The team had a strong second place finish in Ground Tournament 2 (GT-2) in March 2016, the second “ground tournament” of the challenge. The CubeQuest Challenge offers a total of more than $5 million in prizes to teams that develop CubeSats for deep space or lunar orbit. The top three competitors in
The final ground tournament will win a spot on the Space Launch System’s Exploration Mission 1 launch, currently scheduled for 2018. The SLS will deploy more than a dozen CubeSats, most sponsored by NASA or international space agencies, en route to delivering an unmanned Orion crew vehicle to lunar orbit. Two more CubeQuest ground tournaments remain, with the final competition scheduled for February 2017.

The backpack-size MIT spacecraft, a 6U (10 cm x 20 cm x 30 cm) CubeSat called “KitCube,” (the MIT mascot is the beaver, and a “kit” is a baby beaver) features a laser communications payload developed in the Space Telecommunications, Astronomy, and Radiation (STAR) Lab at MIT, and novel green monopropellant propulsion technology. KitCube will compete for the lunar derby prize (successfully entering lunar orbit) as well as the best burst data rate prize. The laser communications payload is expected to achieve a data rate of better than 1.5 Mbps over a 30-minute interval from lunar orbit. Green monopropellant is a less-toxic fuel than commonly-used hydrazine with a relatively high specific impulse. “The KitCube project not only allows students to apply what they learn in the classroom to an actual CubeSat, but also to solve problems that have not truly been solved in this domain,” said AeroAstro graduate student Alison Gibson. “With the intention of demonstrating a novel technology (laser communications) in a lunar orbit obtained using chemical propulsion, KitCube’s goals are very ambitious for such a constrained satellite platform.”

KitCube’s student team is composed of a mix of MIT undergraduate and graduate students, with more than 45 active team members from AeroAstro, Electrical Engineering and Computer Science, and Mechanical Engineering. Since GT-1, KitCube has also teamed up with Project Selene, a team of high school students from La Cañada Flintridge, Calif. “KitCube has allowed us to organize around the common goal of bettering our universe through the application of STEM education, which is imperative in the 21st century,” said high school student Sonya Kalara. The MIT student team began working on the project in the spring semester of 2015 as part of a joint undergraduate/graduate course, and, after only a semester of work, placed second place in GT-1. Since then, students have continued working on the project in the classroom and regularly participate in site visits, teleconferences with industry sponsors, and rigorous safety reviews with NASA personnel. Graduate student David Sternberg said, “As the teaching assistant for the class that created the
KitCube project, I’m excited to see how the current team of both graduates and undergraduates continues to excel at developing a novel system that incorporates technologies with broad application potential beyond the lunar mission.”

MIT’s Team KitCube encourages all interested space enthusiasts at MIT to join the project. “With the goal of sending a small satellite into lunar orbit, KitCube is an outstanding project,” said graduate student Ashley Carlton. “Not only is KitCube advancing state of the art technologies, but it is exclusively led by students, pioneering the way for future satellite engineers!” Individuals can contact kcahoy@mit.edu or crewsab@mit.edu to learn more.

ANGELA CREWS is an MIT AeroAstro PhD candidate and a member of the KitCube team. She may be reached at crewsab@mit.edu.
Rocket Team’s Therion uses electric wind to reduce drag, sails to a landing

by Eric Riehl

The MIT Rocket Team is a student-run organization composed of 40 members who embark on year-long projects to compete in the annual summer Intercollegiate Rocket Engineering Competition.

This year, the team built a rocket we named Therion. It’s 12 feet tall, 6 inches in diameter and designed to reach an altitude of 10,000 feet with its powerful solid motor capable of producing 760 pounds of thrust for more than three seconds. Therion’s fully-custom composite structure experiences more than 14Gs of acceleration as it reaches velocities surpassing 700 mph.
One of Therion’s two payloads is a plasma physics experiment. It’s designed to induce roll torque on the rocket without any moving components. By creating a strong, pulsed electric wind along the surface of four small high angle of attack canards, it changes the aerodynamic characteristics to produce a net torque on the rocket. This is done using a cold plasma discharge (dielectric barrier discharge) excited on kapton and copper electrodes by a flyback transformer operating at 8 kHz. Pulsing the plasma during ascent and measuring the roll rate allows the team to characterize the drag effects across a wide range of velocities.

Therion’s second payload is an imaging experiment that makes use of the Lucas-Kanade method to acquire rotation data by comparing pixel displacement between frames. The data is compared to measurements from an onboard inertial measurement unit to determine its accuracy.

Successful recovery is a critical part of the competition. The recovery system consists of a small drogue parachute, which deploys at apogee to stabilize the vehicle, but not provide so much drag as to cause it to drift with the wind. Once near the ground, a pyrotechnic link is detonated, allowing the drogue to pull out the main parachute so the rocket touches down softly.

The team keeps track of the rocket during its mission with live telemetry updates, which include critical information such as GPS location, altitude, and speed. This also helps the team recover the rocket.

The team launched Therion in June at the 2016 Intercollegiate Rocket Engineering Competition, and achieved 14th place out of 44 teams. The pyrotechnic link, a critical part of the recovery system, did not separate after receiving the signal from onboard avionics, which caused the rocket to touch down using only a drogue chute. The structure held up surprisingly well against the impact, but one broken fin meant it was not in re-flyable condition. At the time of this writing, the team is analyzing the payload results.
NEW TECHNOLOGIES, OUTREACH

Beyond the competition flight, the Rocket Team explores possibilities and creates new technologies for future use. This year, the team spent considerable time on a new recovery system. Rather than deploy round parachutes after separating its structure at apogee and drifting aimlessly, the system uses an actuated parafoil to guide itself autonomously to a selected landing zone. This required extensive study of parafoil dynamics and control, as well as the development of pyrotechnic rope cutters, frangible bolts, hatch and mortar deployment, custom servomechanisms, and redundant avionics built and coded to be failsafe. The new capabilities have expanded the options for projects and solutions in coming years.

The team also sponsors its members to build and launch their own rockets to achieve certification with the National Association of Rocketry. We’ve added eight new people to our considerable number of certified team members. The team is also heavily involved in outreach activities, often joining with the MIT Museum and programs run by the Educational Studies Program. This year, 24 volunteers hosted a Museum-sponsored “Science on Saturday” event with more than 1,000 attendees, mostly elementary school students, who enjoyed a presentation showcasing the basics of rocketry, followed by hands-on activities. The team renovated its Building 17 lab space this year, thanks to the generous support of the AeroAstro Department. The new lab contains needed storage, a composites workstation, an electronics workstation, a parachute-manufacturing station, multiple 3D printers, proper storage for rocket engines, an integration table, and tool racks.

For the first time in its history, the Rocket Team moved to become a professional organization set to continue its legacy by establishing methods to pass down knowledge year to year. This year the team spread itself to develop every aspect and system from scratch, and is now poised to build on top of what was learned to reach new heights.

ERIC RIEHL is president of the MIT Rocket Team and a member of the AeroAstro class of 2017. He may be reached at riehlatmit@gmail.com.
Alumnus Art Samberg (SB ’62), owner of Hawkes Financial and former chairman and chief executive officer of Pequot Capital Management, advises AeroAstro students to “follow your passion.” (William Litant/MIT photograph)
AEROASTRO ALUMNUS INTERVIEW

“Follow your passion”
A conversation with Arthur Samberg

Arthur J. Samberg, owner of Hawkes Financial LLC, is the former chairman and chief executive officer of what was, at one point, the largest hedge fund in the world: Pequot Capital Management. In his current role, he works with his family members to identify investment opportunities regarding, among other things, technology research and development.

Art received an SB from MIT Aeronautics and Astronautics in 1962. He holds an MS in Aeronautics and Astronautics from Stanford University and an MBA from Columbia University.

Prior to launching his finance career, Art worked as an aerospace engineer at the Lockheed Missiles and Space Company where he focused on guidance and control technologies for the Agena missile system.

Art Samberg is a life member emeritus of the MIT Corporation and a member of the Aeronautics and Astronautics Department Visiting Committee. For five years he served as chairman of the MIT Investment Management Company and currently sits on the MIT Energy Initiative Board of Advisors.
When did you first know you were interested in aerospace engineering?

Samberg: My dad graduated high school as the oldest of five in 1929. His father, an immigrant tailor, was thrown out of work and he had to support the family by becoming an electrician. I think I subconsciously wanted to fulfill his dream at an early age. I found myself doodling airplanes while in class. When Sputnik went up in 1957 it blew my mind away. I was hooked on studying aeroastro.

What did you do while at MIT AeroAstro?

Samberg: Enjoyed being an undergraduate at a terrific academic university, meeting really smart people, and trying to grow up. I was most interested in control systems and took elective classes in that area, eventually getting my first job in that area.

What things particularly stand out about your time at MIT/AeroAstro?

Samberg: I was a very average student at MIT. I think throughout the four-year experience I discovered that I could solve the equations, but lacked a real feel for what was going on physically. That just served to make me want to get the most out of the four-year experience in a broad sense.

What have you done since leaving MIT?

Samberg: Upon graduation I took a job at Lockheed Missiles and Space Company in Sunnyvale, Calif. I initially worked in the guidance and control group for the Polaris missile. I became friendly with a guy who had also just graduated from the University of Colorado and worked at Philco Ford. We shared an apartment. He was admitted to Stanford for a master’s program in electrical engineering sponsored by his company. Being competitive, I immediately looked into what Lockheed had to offer. I began my studies for my MS in aeronautics and astronautics in Stanford’s second trimester, graduating in August 1963, one year after getting my MIT degree, while working throughout. The Stanford experience paid off in other ways. I met my wife, Rebecca, who was getting her MS in history, and we married right after I completed my coursework in August. We just celebrated our 53rd anniversary.

After the wedding I went back to Lockheed and worked in a terrific group doing orbital mechanics for various satellites launched off the Agena platform. Although I could do the work, it was becoming increasingly clear to me I would never be great at it. Another benefit of being around Stanford at that time was that two friends from MIT were enrolled in the business school. I developed a real interest in the stock market at that time, importantly influenced by Comsat, the first commercial satellite company, going public.
In September 1965, I moved back to the New York City area where I grew up and enrolled at the Columbia Business School. I accelerated my stay at CBS when we had our first child in July 1966, going through the summer semester, and graduating in December 1966. That son, Jeff, was followed by Laura in 1968, and Joe in 1970.

**How did you make your way from Lockheed to the financial sector?**

**Samberg:** MIT figured in my first job on Wall St. There were very few MIT grads on the street in the late ‘60s. In fact, because of the depression and then World War II, there was a real hollowing out of people overall in the financial markets. The director of research at Kidder, Peabody was Tom Folger (Mechanical Engineering SB ’48, SM ’49), an MIT grad. In a pioneering move, he was determined to build a technology research capability at Kidder; the first, I believe, in the business. Shortly before I got there he had hired Bob Johnson, (Physics ’63) to follow computers and electronics companies. I was assigned aeroastro and also electronics. Bob and I shared an office next to Tom’s. I loved it and loved being a pioneer.

One thing I discovered about myself was a strong entrepreneurial instinct. In 1970, a small start-up money management firm, Weiss, Peck & Greer was founded. I joined them as the first outside professional hire in April. The firm was a great success and I stayed 15 years doing research, joining the management committee, and, for the final five years, managing firm capital.

The entrepreneurial bug I mentioned stayed with me. In 1984, encouraged by superior performance in managing firm capital (30 percent per year for five years), I joined a former WP&G employee, Jon Dawson, who had started an advisory firm, to start a hedge fund. The renamed Dawson, Samberg Capital Management launched Pequot Partners in November 1986 with $3.3 million in assets.

At the time there were perhaps 50 hedge funds in the business. Performance was good, and the fund grew massively. In 1998 the hedge funds spun out into a new firm, Pequot Capital. In early 2000 the Wall St Journal announced that Pequot was the largest hedge fund in the world with $17 billion in assets under management.

**Please tell us more about your current job.**

**Samberg:** As exciting as the ‘90s were, the ‘00s were fraught with disappointments and challenges. In 2000, I had an aortic dissection, a very serious vascular disease. The next year Pequot split into two firms. While trying to build the firm back up I ran into fierce headwinds facing the hedge fund industry. Performance remained good; the 23-year record for the fund exceeded 17 percent compounded annually, despite being down 20 percent in the first year.

The ride was exceptionally rewarding and challenging. I credit my MIT years for preparing me the good times and bad. I have drunk from a fire hose since I was 17, and have learned well how to handle what the world dishes out.
What are your favorite aspects of your job?

Samberg: When I shuttered Pequot in 2009 I opened a family office where I invest in venture capital startups with my two sons. How great is that? When I first went down to Wall Street I believed my value add to the system was to help in the proper allocation of capital. My interest has always been in investing in growth situations, ones that keep America vibrant and create jobs. I am not a “value investor.” Financial markets have changed enormously since I entered the business, and public equity investing has become nowhere as fulfilling in my mind.

By doing venture capital I believe I am taking the best of my early technology training and latter financial skills. One example is a fusion company that I chair that has raised $500 million and is within 18 months of final proof of scientific concept. There are many more, which, while not quite as world changing as fusion, are really cool.

One of the great side benefits is having invested in five startups by MIT people.

How did AeroAstro prepare you for your career?

Samberg: AeroAstro is a multidisciplinary discipline. I learned about many different technologies while studying it. The systems approach is also very similar to attacking a complex financial problem. These fundamental skills have been very useful in how I approach a problem.

Other AeroAstro graduates have taken up careers in finance. What do you think makes MIT engineers particularly suited for this world?

Samberg: It’s been said many times — the MIT and engineering approach is a great background to help you analyze complex problems. I feel my life is a case study in that.

What advice would you offer to high school kids about considering engineering careers?

Samberg: I was an MIT educational counselor for a number of years. First, you have to genuinely like math and science. If you do, what better way to prepare for a world increasingly favoring new technologies that are disrupting whole swaths of industry and life in general?

What advice would you offer to current AeroAstro students to best position themselves for their careers?

Samberg: Follow your passion. Whatever it is, in AeroAstro, in some other science or engineering field, or even in finance!

How do you perceive current career opportunities for those who graduate with an AeroAstro undergrad degree?

Samberg: Not being close to the direct field, it is hard for me to say. When I graduated the race to the moon was on and times were good for an Aero Astro grad. Despite that I went in a different direction and it worked out well. The foundation you have built will lead to something great. Keep moving forward, don’t settle for something you don’t enjoy doing every day.
Your family has supported MIT in various ways over the years, the latest projects including renovating Building 31 and creation of the Samberg Conference Center at E52. How important is reinvesting in infrastructure for MIT’s next 100 years in Cambridge?

Samberg: In addition to those bricks and mortar projects I believe our family has given more scholarship aid than anyone. One is useless without the other. People and bricks, both are essential. That said, the uniqueness of MIT is the lab structure. They are expensive and the work of the future can’t be done with outdated facilities. Other schools are spending aggressively to catch MIT. The world needs us.

What do you like to do in your spare time?

Samberg: A lot of not-for-profit work. I am on the execom at New York Presbyterian Hospital, co-chair of the Columbia Business School, Board of Jazz at Lincoln Center, the New York Genomics Center, and Jacob Burns Film Center. I hung up my basketball sneakers a while ago, but religiously go to my seven grandkids’ games of all sorts. Summers are spent on Lake Michigan where I read, bike, kayak, and just kick back.

Anything else you’d like to tell us?

Samberg: Live life to its fullest, don’t settle for something you aren’t passionate about and care for other people.
Building 31’s new high-bay space will be home to the Center for Autonomous Systems, a place where AeroAstro researchers can conduct research involving flying robotic aerial systems. (William Litant/MIT photograph)
The three projects visible from this vantage point — renovation of Building 31, the Sloan Laboratories for Aircraft and Automotive Engines; Building 9, the Samuel Tak Lee Building; and MIT.nano (the new Building 12) — have hundreds of construction workers, tradespeople, and facilities personnel working around the clock to deliver renewed, modern space for MIT’s students, staff, and faculty.

Most central to the AeroAstro mission is the $52 million Building 31 transformation. The total gutting of Building 31 will clear out much of the legacy equipment no longer used for research, and make space for cutting-edge research in autonomous systems alongside the legendary anchor tenancy of the Gas Turbine Lab. Shared between AeroAstro and Mechanical Engineering, the renovation will add nearly 7,000 square feet of useable space, more than doubling occupant capacity.

“The original Sloan Automotive Lab was constructed in 1928 with multiple additions over the next three decades,” said the renovation’s lead architect Jon Keller, of Imai Keller Moore Architects. “With each addition, new floors were added here and there, and not on the same level as each other. This makes accessibility and connectivity a challenge.”

Keller noted that the building’s infrastructure was antiquated and required updating on all fronts including structural, fire safety, mechanical, electrical, and plumbing. “With these needed improvements, there was great opportunity to create a unique research environment in the center of campus with new labs and offices for both AeroAstro and Mechanical Engineering,” Keller said.
The exhaustive renewal of Building 31’s major systems has nearly 70 workers from 18 trades working together at all times — a feat only possible because of the cooperation of the temporarily displaced occupants. “One of the key factors contributing to the success of this project has been the incredible flexibility of our faculty, students, and staff who have been moved into temporary quarters to allow us to empty the building. This has not only sped up the project, but also helped to lower the overall cost,” said AeroAstro space manager Anthony Zolnik.

Some research activities must continue in the building during renovations, making the project more challenging. Brian Donnellan, an MIT Facilities senior project manager said, “We need to plan around research activities to minimize any impacts experienced with the byproducts of construction, including noise and vibration,”

Sarah Yazici, another senior project manager, added, “A unique and interesting challenge in this renovation is tackling the reconstruction and upgrading of the DeLaval Wind Tunnel System.” The DeLaval operates at supersonic wind speeds with a tunnel structure that runs vertically through the building across all floors of the west wing of 31. Noise mitigation is required throughout.

A key feature of the renovated building will be a new high-bay space housing the Center for Autonomous Systems. This 80-foot-long, 40-foot wide, and 25-foot-high space is nearly the size of a basketball court, will be used for testing of aerial robotic systems, and represents a major upgrade over the current space used for testing aerial autonomous vehicles. The new space is so large that it can be split in half for concurrent research, and will include state-of-the-art motion capture cameras and augmented reality created by overhead projectors that illuminate the floor.
Jon How, the Maclaurin Professor of Aeronautics and Astronautics and head of the Aerospace Controls Laboratory, said, “Motion capture flight spaces have revolutionized recent work on aerial robotics since they were first created at MIT in 2007. The additional floor area will enable quadrotor flight testing at higher speeds, testing of control systems for full-scale fixed-wing aircraft, and much more sophisticated multiagent search and rescue type missions with humans in the loop.”

The new high-bay space and the surrounding support space was made possible by a gift from AeroAstro alumnus Kent Kresa (‘59, SM ‘61, ENG/EAA ‘66). The former Chairman and CEO of Northrop Grumman, Kresa gave the gift to support MIT’s ongoing leadership in autonomous systems and was key in making the full renovation a reality. Several other MIT alumni have supported the Building 31 project, including Art Samberg (AeroAstro ’62) who is interviewed in this issue of AeroAstro.

The grand reopening of Building 31 is slated for the second half of 2017. When the doors reopen, AeroAstro will have renewed more than 50 percent of its research space in fell swoop, thanks to our alumni, faculty, staff, and administration coming together for MIT’s future.

**MARK VELIGOR** is a development officer with the MIT School of Engineering. He raises philanthropic support for projects within the Aeronautics and Astronautics and Biological Engineering departments. He can be reached at mveligor@mit.edu.
Changing the pitch of the Wright Brothers Wind Tunnel’s six wooden blades, shown here in 1938, is one means of controlling the air speed. Nearly 80 years later, the pitch mechanism had worn to the point that a complete rehab was in order. (MIT Museum photograph)
Since September 1938, when it was dedicated during the Fifth International Congress of Applied Mechanics, the Wright Brothers Wind Tunnel has played a key role in the development of aerospace, civil engineering, and architectural systems.

From its early days during World War II, when technicians worked in two shifts on military aircraft design, testing has evolved to today’s examination of ground antenna configurations, aero-elastic dynamics of airport control tower configurations, ski gear, space suits, bicycle and motorcycle configurations, subway station entrances, ship sails, wind turbines, and a design for a clean, quiet, and super-efficient commercial aircraft.

When MIT dedicated WBWT it was capable of a 400 mph top speed. The story has it that it was only operated at that speed a few times; the noise was deafening and MIT received complaints from across the river in Boston.

In recent years, the department has seldom pushed the tunnel above about 180 mph. But during the summer of 2015, it became obvious something was wrong. “We couldn’t get it over 40 mph,” says AeroAstro technical instructor David Robertson, who had just assumed the tunnel’s management. “We couldn’t repeat speeds and the times required to change from one speed to another were all over the place.”
WBWT wind speeds are controlled in two ways: The 1 megawatt DC electric motor that spins the tunnel fan has three fixed rotational speeds and the pitch of the six (length) wooden blades may be varied. Something was preventing the blades from changing pitch. “We ruled out electrical problems,” Robertson said. “You could hear the pitch motor laboring.”

The blade pitch is controlled by a small electric motor that actually spins with the fan. The motor operates a series of six planet gears that turn inside a larger sun gear. The sun gear, in turn, rotates six more gears that, through a worm-and-gear system, simultaneously twists each blade. Robertson believes it had been at least 30 years since the pitch control was last serviced.
Robertson and Gas Turbine Lab manager James Letendre tried cleaning and greasing the mechanism in-situ. Working in the depths of the tunnel during the height of summer was “like working in a pizza oven wearing a toaster-oven hat,” Robertson said. With the sun beating down on the outside of the big steel tube, inside temps can easily exceed 110F.

Still, the tunnel refused to operate properly. Consulting with WBWT director Professor Mark Drela, Robertson and Letendre realized there was no other option — the blades would have to come out and the pitch transmission disassembled.

Over a period of several days during December 2016, the blades were hoisted through a hatch in the tunnel top and carried into the WBWT control room, where they were cleaned and greased. Under the guidance of technical instructor Todd Billings, who manages AeroAstro’s Gelb Laboratory machine shop, and with the aid of the original blueprints, the gear mechanism was removed, disassembled and inspected.

The good news was that after nearly eight decades, the gears themselves were in perfect condition. The problem was the shafts on which the planet gears were mounted. The inner races of bearing sets that were pressed to the shafts had worked loose, wearing down the shafts and allowing the gear sets and shafts to shift laterally.

One down, five to go: space manager Anthony Zolnik steadies a blade from above while (from left) Professor Mark Drela, Jim Letendre, and Dave Robertson prepare to carry it off. (William Litant/MIT photograph)
Machining new shafts required equipment not available in the AeroAstro shop, so Billings had them produced in MIT’s Central Machine Shop. As the orientation of the gears is critical, when the new shafts arrived, the transmission had to be temporarily reassembled and mounted in the tunnel. Robertson and Billings designed and built a jig that marked where securing keyways should be machined. Once again, working in the dark, cramped confines of the tunnel, the team disassembled the transmission, sent it back for final machining, and then put it all back together and refitted the blades. Finally, the blades had to be synced so all six would be in the same position as the pitch is varied. Robertson made a tool that greatly simplified and expedited what would have been a laborious task.

While this was going on, Robertson sent the 250-volt pitch control motor out for rebuilding. “I told the rebuilder that we have all the original part numbers for the motor, but he told me the maker changed the numbers — in 1952,” Robertson laughed.
Just before the Monday, April 18, 2016 Patriots’ Day holiday, Robertson and Drela fired up the motor, operated the pitch mechanism, and it worked perfectly. Timing was also important as the following Saturday was MIT’s campus-wide open house celebrating the 100th anniversary of the Cambridge Campus and WBWT is always an MIT open house main attraction. Thanks to Robertson, Letendre, Billings, and Drela (and with the additional assistance of research specialist Paul Bauer and department space manager Anthony Zolnik) hundreds of visitors experienced standing in the operating tunnel, where they each received a special certificate designating them a “Distinguished Wind Tunnel Model Subject.”

In the not-too-distant future, the AeroAstro Department expects to launch a campaign to completely refurbish the WBWT and its associated mechanical systems and instrumentation. And, for the foreseeable future the venerable tunnel will continue to serve as an unparalleled teaching and research facility for MIT students, staff, and faculty.

**WILLIAM T.G. LITANT** is the AeroAstro director of communications. He may be reached at wlitant@mit.edu.
Aboard a parabolic aircraft flight, Man Vehicle Lab grad student Pierre Bertrand conducts experiments in reduced-gravity astronaut maneuvering. (Novespace/CNES photograph)
AEROSPACE COMPUTATIONAL DESIGN LABORATORY

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

Advanced simulation methods developed by ACDL researchers facilitate the understanding and prediction of physical phenomena in aerospace systems and other applications. The lab has a long-standing interest in advancement of computational fluid dynamics for complex three-dimensional flows, enabling significant reductions in time from geometry to solution. Specific research interests include aerodynamics, aeroacoustics, flow control, fluid structure interactions, hypersonic flows, high-order methods, multi-level solution techniques, large eddy simulation, and scientific visualization. Research interests also extend to chemical kinetics, transport-chemistry interactions, and other reacting flow phenomena important for energy conversion and propulsion.

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

ACDL research in simulation-based design and control is aimed at developing methods to support better decision-making in aerospace and other complex systems, with application to conceptual, preliminary, and detailed design. Recent efforts yielded effective approaches to PDE-constrained optimization, real time simulation and optimization of systems governed by PDEs, multiscale and multi-fidelity optimization, model order reduction, geometry management, and fidelity management. ACDL applies these methodologies to aircraft design and to the development of tools for assessing aviation environmental impact.

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

Visit the Aerospace Computational Design Laboratory at acdl.mit.edu

AEROSPACE CONTROLS LABORATORY

The Aerospace Controls Laboratory researches autonomous systems and control design for aircraft, spacecraft, and ground vehicles. Theoretical research is pursued in such areas as decision making under uncertainty; path planning, activity, and task assignment; mission planning for unmanned aerial vehicles; sensor network design; and robust, adaptive, and nonlinear control.

A key aspect of ACL is RAVEN (Real-time indoor Autonomous Vehicle test ENVironment), a unique experimental facility that uses a motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and aircraft, and robust coordination algorithms for multiple vehicles; and ground projection system that enables real time animation of the planning environ-
ment, beliefs, uncertainties, intentions of the vehicles, predicted behaviors (e.g., trajectories), and confidence intervals of the learning algorithms. Recent research includes the following:

**Robust Planning in Uncertain Environments:** ACL developed consensus-based bundle algorithm (CBBA) as a distributed task-planning algorithm that provides provably good, conflict-free, approximate solutions for heterogeneous multi-agent missions. Aside from extensions to task time-windows, coupled agent constraints, asynchronous communications, and limited network, CBBA has been validated in real-time flight test experiments. ACL has also extended its development of chance-constrained rapidly-exploring random trees (CC-RRT), a robust planning algorithm to identify probabilistically feasible trajectories, to new aerospace applications.

In a May 2016 ceremony, Lockheed Martin CTO Keoki Jackson (center, left) AeroAstro ’89, SM ’92, ScD ’97, and MIT AeroAstro department head Jaime Peraire congratulate each other after signing a research collaboration agreement between the two organizations. Initial research will focus on robotics and autonomous systems, and be conducted professors AeroAstro professors Jonathan How, Nick Roy, Sertac Karaman, Julie Shah, and Russ Tedrake, and Department of Mechanical Engineering Professor Sangbae Kim. (William Litant/MIT photograph)
domains. For instance, ACL recently developed CC-RRT to solve robust pursuit-evasion problems. ACL is also involved in a multi-year Draper URAD on precision landing of guided parafoils, with robustness to large and dynamic wind environments. Finally, ACL is participating in a multi-year MURI focused on enabling decentralized planning algorithms under uncertainty. Ongoing ACL research has demonstrated that the use of flexible nonparametric Bayesian models for learning models of uncertain environment can greatly improve planning performance.

**UAV Mission Technologies:** ACL has recently demonstrated autonomous, closed-loop UAV flight in MIT’s Wright Brothers’ Wind Tunnel. This novel capability allows the ACL to test flight controllers for windy environments in a controlled and systematic manner. ACL has also developed a novel hovering vehicle concept capable of agile, acrobatic maneuvers in cluttered indoor spaces. The vehicle is a quadrotor whose rotor tilt angles can be actuated, enabling upside-down hovering flight with appropriate control algorithms. Additionally, as part of research on long-duration UAV mission planning, ACL has constructed an autonomous recharge platform, capable of autonomous battery replacement and recharging for small UAVs. This capability allows ACL to demonstrate complex, multi-agent missions lasting for several hours.

**Information-Gathering Networks:** Recent ACL research has addressed maximizing information gathering in complex dynamic environments, through quantifying the value of information and the use of mobile sensing agents. The primary challenge in such planning is the computational complexity, due to both the large size of the information space and the cost of propagating sensing data into the future. ACL researchers created adaptive efficient distributed sensing in which each sensor propagates only high value information, reducing the network load and improving scalability. Recently-developed algorithms embed information planning within RRTs to quickly identify safe information-gathering trajectories for teams of sensing agents, subject to arbitrary constraints and sensor models.

**Task Identification and Decision-Making:** Markov Decision Processes (MDP) and Partially Observable MDPs (POMDP) are natural frameworks for formulating many decision-making problems of interest. ACL has identified approximate solution techniques which can utilize this framework while lessening the curse of dimensionality and the curse of history typically encountered for exact solutions. ACL has also developed a Bayesian Nonparametric Inverse Reinforcement Learning algorithm for identifying tasks from traces of user behavior. This technique allows a user to “teach” a task to a learning agent through natural demonstrations. ACL has also enabled fast, real-time learning in combination with cooperative planning in uncertain and risky environments, while maintaining probabilistic safety guarantees for the overall system behavior. Finally, by efficiently using potentially inaccurate models of physical systems, ACL has developed a method that minimizes samples needed in real-world learning domains such as a car learning to race around a track.

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

ACL faculty are professors Jonathan How and Steven Hall.

Visit the Aerospace Controls Laboratory at acl.mit.edu

AEROSPACE ROBOTICS AND EMBEDDED SYSTEMS GROUP

The Aerospace Robotics and Embedded Systems group’s mission is the development of theoretical foundations and practical algorithms for real-time control of large-scale systems of vehicles and mobile robots. Application examples range from UAVs and autonomous cars, to air traffic control, and urban mobility. The group researches advanced algorithmic approaches to control high-dimensional, fast, and uncertain dynamical systems subject to stringent safety requirements in a rapidly changing environment. An emphasis is placed on the development of rigorous analysis, synthesis, and verification tools to ensure the correctness of the design. The research approach combines expertise in control theory, robotics, optimization, queuing theory and stochastic systems, with randomized and distributed algorithms, formal languages, machine learning, and game theory.

Current research areas include the following:

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

» Affordable autonomy: can we design safe and reliable self-driving vehicles at a cost that make them affordable for the general public? Our demo vehicles at the Singapore-MIT Alliance for Research and Technology were developed with less than $30,000 worth of computers and sensors.

» Provable safety: how do we make sure that the vehicle will behave safely, and respect all the rules of the road? We developed algorithms that provably satisfy all “hard” rules, while minimizing violations of “soft” rules or recommendations.

» Autonomy for mobility-on-demand: How would self-driving vehicles impact urban mobility in the future? We envision fleets of shared self-driving vehicles, develop algorithms for their sizing and operations, and analyze their effects using real data from several cities worldwide.

Real-time motion planning and control: The group is developing state-of-the art algorithms for real-time control of highly maneuverable aircraft, spacecraft, and ground vehicles. Focus areas include optimality and robustness, as well as provable safety and correctness with respect to temporal-logic specifications (e.g., rules of the road, rules of engagement). Current projects include high-speed flight in cluttered environments and high-speed off-road driving.

Multi-agent systems: Large, heterogeneous groups of mobile vehicles, such as UAVs and UGVs, are increasingly used to address complex missions for many applications, ranging from national security to environmental monitoring. An additional emphasis in this work is scalability; our objective is not only the design of distributed algorithms to ensure provably efficient and safe execution of the assigned tasks, but also to understand exactly how the collective performance and implementation complexity scale as the group’s size and composition change.
Transportation networks: Traffic congestion, and extreme sensitivity to, for example, environmental disruptions, is a well-known effect of increasing access to transportation. As infrastructure development saturates, new approaches are necessary to increase the safety, efficiency, and environmental sustainability of transportation networks. The group’s research in this area concentrates on the exploitation of real-time information availability through wireless communications among vehicles, and with existing infrastructure, to achieve this goal.

Emilio Frazzoli directs the Aerospace Robotics and Embedded Systems group.

Visit the Aerospace Robotics and Embedded Systems group at ares.lids.mit.edu

THE AUTONOMOUS SYSTEMS LABORATORY
The Autonomous Systems Laboratory is a virtual lab led by professors Brian Williams and Nicholas Roy. Williams’ group, the Model-based Embedded and Robotic Systems (MERS) group, and Roy’s Robust Robotics Group are part of the Computer Science and Artificial Intelligence Lab. ASL work is focused on developing autonomous aerospace vehicles and robotic systems. ASL-developed systems are commanded at a high-level in terms of mission goals. The systems execute these missions robustly by constantly estimating their state relative to the world, and by continuously adapting their plan of action, based on engineering and world models.

Below are several recent demonstrations.

» Operating autonomous vehicles to maximize utility in an uncertainty environment, while operating within acceptable levels of risk. Autonomous underwater vehicles enable scientists to explore previously uncharted portions of the ocean, by autonomously performing science missions of up to 20 hours long without the need for human intervention. Performing these extended missions can be a risky endeavor. Researchers have developed robust, chance-constraint planning algorithms that automatically navigate vehicles to achieve user specified science goals, while operating within risk levels specified by the users. (Video at csail.mit.edu/videoarchive/research/robo/auv-planning)

» Human-robot interaction between a robotic air taxi and a passenger. The task is for the autonomous vehicle to help the passenger rethink goals when they no longer can be met. Companies like the MIT spinoff Terrafugia offer vehicles that can fly between local airports and can travel on local roads. To operate these innovative vehicles, one must be trained as a certified pilot, thus limiting the population that can benefit from this innovative concept.

In collaboration with Boeing, MERS has demonstrated in simulation the concept of an autonomous personal air vehicle in which the passenger interacts with the vehicle in the same manner that they interact today with a taxi driver. (Video at csail.mit.edu/videoarchive/research/robo/personal-aerial-transportation.)

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

ASL faculty are Brian Williams and Nicholas Roy. Visit the Model-based Embedded Systems group at mers.csail.mit.edu and the Robust Robotics Group at groups.csail.mit.edu/rrg

COMMUNICATIONS AND NETWORKING RESEARCH GROUP

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

Over the past few years, the group has been developing efficient network control algorithms for wireless networks (e.g., flow-control, routing, link scheduling). A recent focus has been on the design practical network control algorithms, based on the theories developed by Professor Eytan Modiano and his students over the last decade. These algorithms have been shown to optimize network performance (e.g., maximize throughput and utility) but so far have been largely limited to being a theoretical framework. With funding from the DoD and NSF, the group has turned its attention to the design of algorithms that take into account practical considerations such as hardware limitations, the need for distributed operations, and inter-operability with legacy systems. This new focus will facilitate the adaptation of these schemes into networks used in practice.

Robust network design is another exciting area of recent pioneering research by the group. In particular, the group has been developing a new paradigm for the design of highly robust networks that can survive a massive disruption that may result from natural disasters or intentional attack. The work examines the impact of large-scale failures on network survivability and design, with a focus on interdependencies between different networked infrastructures, such as telecommunication networks, social networks, and the power grid. The group’s research crosses disciplinary boundaries by combining techniques from network optimization, queueing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Eytan Modiano directs the Communications and Networking Research Group.

Visit the Communications and Networking Research Group at cnrg.mit.edu

GAS TURBINE LABORATORY

The Gas Turbine Laboratory’s mission is to advance the state-of-the-art in fluid machinery for power and propulsion. The research is focused on advanced propulsion systems, energy conversion and power, with activities in computational, theoretical, and experimental study of loss mechanisms and unsteady flows in fluid machinery, dynamic behavior and stability of compression systems, instrumentation and diagnostics, advanced centrifugal compressors and pumps for energy conversion, gas turbine engine and fluid machinery noise reduction and aero-acoustics, novel aircraft and propulsion system concepts for reduced environmental impact.
Current research projects include:

» a unified approach for vaned diffuser design in advanced centrifugal compressors
» investigation of real gas effects in supercritical CO2 compression systems
» modeling instabilities in high-pressure pumping systems
» aeromechanic response in a high performance centrifugal compressor stage ported shroud operation in turbochargers
» manifestation of forced response in a high performance centrifugal compressor stage for aerospace applications
» multiparameter control for centrifugal compressor performance optimization
» performance improvement of a turbocharger twin scroll type turbine stage
» a two-engine integrated propulsion system
» propulsor design for exploitation of boundary layer ingestion
» aerodynamics and heat transfer in gas turbine tip shroud cavity flows
» secondary air interactions with main flow in axial turbines
» compressor aerodynamics in large industrial gas turbines for power generation
» flow and heat transfer in modern turbine rim seal cavities
» modeling cavitation instabilities in rocket engine turbopumps
» diagnostics and prognostics for gas turbine engine system stability characterization

In December 2015, Gas Turbine Lab faculty, staff, and students gathered for a last group holiday card photo in the “old” Building 31 before the $52 million renovation project ramped up. (William Litant/MIT photograph)
INTERNATIONAL CENTER FOR AIR TRANSPORTATION

The International Center for Air Transportation 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, Peter Belobaba, and Amedeo Odoni.

Visit the International Center for Air Transportation at icat.mit.edu

LABORATORY FOR AVIATION AND THE ENVIRONMENT

Ian A. Waitz, now dean of the MIT School of Engineering, founded the Laboratory for Aviation and the Environment as the Aero-Environmental Research Laboratory in the 1990s.
One of the aviation industry’s defining challenges is addressing aviation’s environmental impact in terms of noise, air quality and climate change. LAE’s goal is to align the trajectory of aerospace technology and policy development with the need to mitigate these impacts. It does so by increasing understanding of the environmental effects of aviation by developing and assessing fuel-based, operational and technological mitigation approaches and by disseminating knowledge and tools. LAE also contributes to cognate areas of inquiry in aerospace, energy, and the environment.

LAE researchers are analyzing environmental impacts and developing research tools that provide rigorous guidance to policymakers who must decide among alternatives when addressing aviation’s environmental impact. The MIT researchers collaborate with international teams in developing aircraft-level and aviation system-level tools to assess the costs and benefits of different policies and mitigation options.

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

LAE has developed and publicly released a code that allows for modeling and evaluation emissions and their impacts throughout the troposphere and stratosphere in a unified fashion. LAE has also recently released a new global emissions dataset for civil aviation emissions, which represents the most current estimate of emissions publicly available. It is widely used by researchers worldwide, in areas including atmospheric modeling and aviation and the environment.

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

LAE faculty include Steven Barrett, director; Robert Malina, associate director; Ray Speth, associate director; Hamsa Balkrishnan; John Hansman; Jayant Sabnis; Ian Waitz; and Karen Willcox. Also associated with LAE are postdoctoral associates Akshay Ashok, Philip Wolfe, and Brian Yutko.

Visit LAE at lae.mit.edu

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

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

Dating to 1939, LIDS has been at the forefront of major methodological developments, relevant to diverse areas of national and worldwide importance, such as telecommunications, information technology, the automotive industry, energy, defense, and human health. Building on past innovation and bolstered by a collaborative atmosphere, LIDS members continue to make breakthroughs that cut across traditional boundaries.

Members of the LIDS community share a common approach to solving problems and recognize the fundamental role that math-
mathematics, physics, and computation play in their research. Their pursuits are strengthened by the laboratory’s affiliations with colleagues across MIT and throughout the world, as well as with leading industrial and government organizations.

LIDS is based in MIT’s Stata Center, a dynamic space that promotes a high level of interaction within the lab and with the larger MIT community. AeroAstro faculty affiliated with the laboratory are Emilio Frazzoli, Jonathan How, Eytan Modiano, and Moe Win.

Visit LIDS at lids.mit.edu

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. It includes:

» The Concept Forum — a multipurpose room for meetings, presentations, lectures, videoconferences and collaboration, distance learning, and informal social functions. In the Forum, students work together to develop multidisciplinary concepts, and learn about program reviews and management.

» Al Shaw Student Lounge — a large, open space for social interaction and operations.

Arthur and Linda Gelb Laboratory. Located in the building’s lower level, the Gelb Laboratory includes the Gelb Machine Shop, Instrumentation Laboratory, Mechanical Projects Area, Projects Space, and the Composite Fabrication-Design Shop. The Gelb Laboratory provides facilities for students to conduct hands-on experiential learning through diverse engineering projects starting as first-year students and continuing through the last year. The Gelb facilities are designed to foster teamwork with a variety of resources to meet the needs of curricular and 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 take considerable floor and table space. Typical of these projects are planetary rovers, autonomous vehicles, and re-entry impact experiments. The structure also houses low-speed and supersonic wind tunnels. A balcony-like mezzanine level is used for multi-semester engineering projects, such as the experimental three-term senior capstone course.

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

The Man Vehicle Laboratory improves the understanding of human physiological and cognitive capabilities as applied to human-vehicle and human-robotic system safety and efficacy, as well as decision-making augmented by technological aids. MVL develops countermeasures and display designs to aid pilots, astronauts, clinicians, patients, soldiers, and others. Research is interdisciplinary and uses techniques from manual and supervisory control, signal processing, estimation, robotics, sensory-motor physiology, sensory and cognitive psychology, biomechanics, human factors engineering, artificial intelligence, and biostatistics. MVL has flown experiments on the Space Shuttle, the Mir Space Station, and on many parabolic flights, and developed experiments for the International Space Station.

Space applications include advanced space suit design and dynamics of astronaut motion, adaptation to rotating artificial gravity, mathematical models for human spatial disorientation, accident analysis, artificial intelligence, and space telerobotics training. Ongoing work includes the development of countermeasures using a short radius centrifuge, 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 UC Davis on customized and just-in-time space telerobotics refresher training. Non-aerospace projects include GE locomotive cab automation and displays, advanced helmet designs for brain protection in sports and against explosive blasts, the development of wearable sensor systems and data visualizations for augmenting clinical decision-making, and data fusion for improving situation awareness for dismounted soldiers.

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

MVL faculty include Professor Jeffrey Hoffman and Professor Leia Stirling, co-directors; Professor Emeritus Laurence Young; Dr. Chuck Oman; and Professor Julie Shah. They teach sub-
jects in human factors engineering, space systems engineering, real-time systems and software, space policy, flight simulation, space physiology, aerospace biomedical engineering, the physiology of human spatial orientation, statistical methods in experimental design, and leadership. The MVL also serves as the office of the director for the NSBRI-sponsored HST Graduate Program in Bioastronautics (Young), the Massachusetts Space Grant Consortium (Hoffman).

Visit the Man Vehicle Laboratory at mvl.mit.edu

NECSTLAB

The necstlab (pronounced “next lab”) research group explores new concepts in engineered materials and structures, with a focus on nanostructured materials. The group’s mission is to lead the advancement and application of new knowledge at the forefront of materials and structures understanding, with research contributions in both science and engineering. Applications of interest include enhanced aerospace advanced composites, multifunctional attributes of structures such as damage sensing, and microfabricated (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 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, AFOSR, ARO, NASA, NIST, NSF, ONR, 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 the fall of 2014, the group moved into new laboratory space in MIT Building 35.

Examples of current and past research projects include:

» efficient deicing of aircraft wings with integrated carbon nanotube based heaters
» out-of-autoclave curing of composites with aligned carbon nanotube heating
» BioNEMS materials design and implementation in microfluidics
» buckling mechanics
» carbon nanostructure synthesis from non-traditional 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 Professor Brian L. Wardle, director; Professor John Dugundji, emeritus; and visitor Antonio Miravete.

Visit necstlab at necstlab.mit.edu

SPACE PROPULSION LABORATORY

The Space Propulsion Laboratory 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 far away places. Areas of research include plasma engines and plumes, and their interaction with spacecraft and thruster materials, and numerical and experimental models of magnetic cusped thrusters. SPL also has a significant role in designing and building microfabricated electrospray thrusters, including their integration into space missions. In addition to providing efficient propulsion for very small satel-
lites 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 monoenergetic molecular ion beams in focusing columns for materials structuring and characterization at the nano-scale and also applications in vacuum technology. 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 and a laser micromachining facility.

SPL faculty are Professor Paulo Lozano, director; and Professor Manuel Martinez-Sanchez, emeritus.

Visit the Space Propulsion Lab at mit.edu/aeroastro/labs/spl

SPACE SYSTEMS LABORATORY

The Space Systems Laboratory 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 struc-
tural control; space power and propulsion; modular space systems
design; micro-satellite design; real-time embedded systems; soft-
ware development; and systems architecting.

SSL has a unique facility for space systems research, the Synchron-
ized Position Hold Engage and Reorient Experimental Satellites
(SPHERES). The SPHERES facility is used to develop proximity
satellite operations such as inspection, cluster aggregation, col-
losion 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 STEM outreach through an exciting program called Zero
Robotics (zerorobotics.mit.edu), which engages high school and
middle school students in a competition aboard the ISS using
SPHERES. It has expanded to more than 100 U.S. and 50 European
teams annually. The finals of the competition run aboard the ISS
by Russian cosmonauts and USA and/or ESA astronauts.

There have been additional exciting hardware augmentations
to SPHERES. Based on the Visual Estimation for Relative Tracking
and Inspection of Generic Objects (VERTIGO) program (from
2012), a cadre of Universal Docking Ports and Halos “expansion
ports” are now aboard the ISS and awaiting operations. The
Universal Docking Ports enable active docking and undocking of
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 REXIS (REgolith
X-ray Imaging Spectrometer) student collaboration instrument
to NASA’s next New Frontiers mission: OSIRIS-REx (Origins,
Spectral Interpretation, Resource Identification, Security Regoli-
th Explorer). The mission is an asteroid sample return mission
to visit the Near-Earth Asteroid Bennu. REXIS is one of five in-
struments onboard and uses a 2x2 array of Lincoln Laboratory
designed charged-coupled devices to measure the X-ray fluores-
cence 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 concen-
trations in the regolith. Professor Richard Binzel, who maintains
a joint MIT EAPS–AeroAstro appointment, and Dr. Rebecca Mas-
terson are leading the project in collaboration with EAPS, Kavli
Institute, and Harvard College Observatory. Over the course of
the project REXIS has included the work of more than 50 under-
graduate and graduate students. The instrument was successfully
integrated to the OSIRIS-REx spacecraft in December 2015. The
REXIS student team supported ATLO (Assembly, Test, and Launch
Operations) at Lockheed Martin and is wrapping up testing
at Kennedy Space Flight Center. The OSIRIS-REx spacecraft
launched in September 2016 and is now on a 2.5-year journey to
the asteroid Bennu.

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

Visit the Space Systems Laboratory at ssl.mit.edu
The Space Telecommunications, Radiation, and Astronomy Laboratory, or STAR Lab, is part of the Space Systems Lab. We focus on developing instruments and platforms that enable weather sensing on Earth and other planets, including exoplanets, and monitoring “space weather” — the highly energetic flow of radiation, or charged particles, that is constantly streaming towards Earth from the sun. This includes development of several shoebox-sized and backpack-sized small satellites, called “CubeSats” for weather sensing and technology demonstration work, particularly in laser communications, as well as work on much larger Hubble-sized space telescopes for direct imaging of exoplanets.

**Weather sensing CubeSat Projects**

- Microsized Microwave Atmospheric Satellite (MicroMAS): MicroMAS-1 was MIT’s first student shoebox-size 3U CubeSat, in collaboration with Dr. 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 are building two MicroMAS-2 CubeSats for relflight in 2017.

- Microwave Radiometer Technology Acceleration mission (MiRaTA). MiRaTA, sponsored by the NASA Earth Science Technology Office, is a joint effort between MIT Lincoln Laboratory, The Aerospace Corporation, the University of Massachusetts 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 is in final stages of integration and test, and is scheduled for delivery in fall 2016 for a winter 2017 launch.

- TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats). Recently selected by NASA’s Earth Venture Instrument program, we will be part of the MIT Lincoln Laboratory-led TROPICS team, building 12 MicroMAS-like CubeSats with microwave radiometer payloads.

**Technology demonstration CubeSat Projects**

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

- KitCube: is a backpack-size (6U) CubeSat that is crowd-funded and part of NASA’s CubeQuest Challenge. Our student team, along with high school team members and industry mentors, is competing for one of three slots to fly a laser communications payload and a green monopropellant thruster-equipped spacecraft to the Moon with the Space Launch System Exploration Mission 1.

- Deformable Mirror Demonstration Mission (DeMi): DeMi will fly a MEMS deformable mirror and compact wavefront sensor on a 6U CubeSat in low Earth orbit, to characterize
mirror performance. These MEMS deformable mirrors can play key roles in wavefront control systems on larger space telescopes to enable high contrast exoplanet imaging.

» FLARE (Free-space Lasercom and Radiation Experiment): FLARE is part of AFRL’s University Nanosatellite Program 9, and will fly two 3U CubeSats, containing both a laser communications transmitter and receiver as well as an energetic particle spectrometer. We will collaborate with Professor Paulo Lozano in the Space Propulsion Laboratory on FLARE’s thruster system.

**Bigger Space Telescopes for Exoplanet Science**

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

The STAR Lab is directed by Professor Kerri Cahoy.

Visit the STAR Lab at starlab.mit.edu

**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 and context in order to maximize their lifecycle value. SERG focuses on research and teaching of Systems Engineering 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 software environment has been used for modeling and simulation of future space exploration campaigns going back to the NASA Constellation program and more recently the Evolvable Mars Campaign. SpaceNet 2.5r is available under a GNU open license and performs detailed network and trajectory analysis, propulsion and logistics calculations and feasibility checks for proposed campaigns. HabNet is a new space habitation modeling and simulation environment that quantifies the flow of resources such as water, gases, propellants, foods, spares, and crew through closed or semi-closed habitat systems. The framework allows the conduct of technology sensitivity analysis for environmental control and life support systems as well as in-situ resource utilization. Our publications in the 2015-2016 timeframe include the feasibility analysis of the proposed MarsOne one-way campaign to Mars, which was the most-downloaded article at MIT’s DSpace repository and has led to over 500 media stories. We also developed and presented a proposal at NASA HQ for use of lunar produced propellants as an enabler of sustained human Mars campaigns with up to 68 percent mass savings compared to the current NASA Design Reference Architecture 5.0 campaign.

SERG also studies the future of infrastructure systems on Earth including multimodal transportation networks, water supply systems, electrical networks and agricultural systems. In 2015-2016 we published a new Generalized Multi-Commodity Network Flow approach that optimizes systems where multiple types of interacting flows exist. Our future work will incorporate distributed satellite missions for earth science with network-based systems design under uncertainty, as well as the modular design of platform-based systems for future aerospace and defense applications.

Awards and recognitions received in 2015-2016 include a Reviewer’s Favorite Choice Award at the ICED 2015 Conference, a Best Paper at the Annual Simulation Symposium at SpringSim’16, and a Best Paper Award at the 26th INCOSE International Symposium.
Current funding sources include NASA, DARPA, Google, Draper Laboratory, U.S. Navy, King Abdulaziz City for Science and Technology. MIT collaborators include the Institute for Data, Systems, and Society; Sociotechnical Systems Research Center; Technology and Policy Program; Center for Complex Engineering Systems; System Design and Management; and Leaders for Global Operations.

The Strategic Engineering Research Group is directed by Professor Oli de Weck.

Visit the Strategic Engineering Research Group at strategic.mit.edu

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 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 pre-defined 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. LSSR has participants from multiple engineering disciplines and MIT schools as well as collaborators at other universities and in other countries. Students are working on safety in aviation (aircraft and air transportation systems, unmanned aircraft, air traffic control), spacecraft, medical devices and healthcare, automobiles, nuclear power, defense systems, energy, and large manufacturing/process facilities. Cross-discipline topics include:

» hazard analysis
» accident causality analysis and accident investigation
» safety-guided design
» human factors and safety
» integrating safety into the system engineering process
» identifying leading indicators of increasing risk
» certification, regulation, and standards
» the role of culture, social, and legal systems on safety
» managing and operating safety-critical systems

We have discovered that our safety techniques are also effective for security, and we are now involved in cyber security and physical (nuclear) security in work for the DoD, FAA, and DoE.

The System Engineering Research Lab is directed by Professor Nancy Leveson. Dr. John Thomas is an SRL-affiliated research engineer.

Visit the System Engineering Research Lab at sunnyday.mit.edu/safety.html

TECHNOLOGY LABORATORY FOR ADVANCED MATERIALS AND STRUCTURES

A dedicated and multidisciplinary group of researchers constitute the Technology Laboratory for Advanced Materials and Structures. They work cooperatively to advance the knowledge base and understanding that will help facilitate and accelerate advanced materials systems development and use in various ad-
vanced structural applications and devices.

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

» composite tubular structural and laminate failures
» MEMS-scale mechanical energy harvesting modeling, design, and testing
» MEMS device modeling and testing, including bioNEMS/MEMS
» structural health monitoring system development and durability assessment
» thermostructural design, manufacture, and testing of composite thin films and associated fundamental mechanical and microstructural characterization
» continued efforts 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 Professor Paul A. Lagacé, Professor John Dugundji (emeritus), and visitor Antonio Miravete.

Visit the Technology Laboratory for Advanced Materials and Structures at mit.edu/telams

WIRELESS COMMUNICATION AND NETWORK SCIENCES GROUP

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

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

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

Lab students are also investigating physical-layer security in large-scale wireless networks. Such security schemes will play increasingly important roles in new paradigms for guidance, navigation, and control of unmanned aerial vehicle networks. The framework they have developed introduces the notion of a secure communications graph, which captures the information-theoretically secure links that can be established in a wireless network. They have characterized the s-graph in terms of local and global connectivity, as well as the secrecy capacity of connections. They also proposed various strategies for improving secure connectivity, such as eavesdropper neutralization and sectorized transmission. Lastly, they analyzed the capability for secure communication in the presence of colluding eavesdroppers.

To advocate outreach and diversity, the group is committed to attracting undergraduates and underrepresented minorities, giving them exposure to theoretical and experimental research at all levels. For example, the group has a strong track record for hosting students from both the Undergraduate Research Opportunities Program and the MIT Summer Research Program (MSRP). Professor Win 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, National University of Singapore, Nanyang Technological University in Singapore, Draper Laboratory, the Jet Propulsion Laboratory, and Mitsubishi Electric Research Laboratories.

Professor Moe Win directs the Wireless Communication and Network Sciences Group.

Visit the Wireless Communication and Network Sciences Group at wgroup.lids.mit.edu
**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 Federal Aviation Authority, 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 nearly 80 years of operation, Wright Brothers Wind Tunnel work has been recorded in hundreds of theses and more than 1,000 technical reports.

In recent years there had been a growing problem with the mechanism controlling the tunnel fan’s blade pitch, which enables researchers to vary the air speed. During the spring of 2016, the blades and the original 77-year-old pitch gear and motor set were removed, refurbished, and reinstalled by a team comprising technical instructors Dave Robertson and Todd Billings, Gas Turbine Lab manager Jim Letendre, and Professor Mark Drela. The tunnel was returned to full operation in time for the Institute’s April 23 Open House, where it was a star attraction for thousands of visitors.

WBWT faculty and staff include Professor Mark Drela and technical instructor David Robertson. Outreach activities are coordinated by communications director William Litant.

Visit the Wright Brothers Wind Tunnel at aeroastro.mit.edu/wbwt