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AEROASTRO

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Cover: Ph.D. candidate Buddy Michini prepares the Humans and Automation Lab's Deck Course of Action Planner real-time demo in the Aerospace Controls Laboratory RAVEN infrastructure. The setup couples a detailed aircraft carrier simulation with robotic ground vehicles representing aircraft motion on a scaled carrier deck. This enables real-time, operator-interactive mission testing of the planning and feedback algorithms being developed by the Action Planner team. See article, p. 17 (William Litant/MIT photo)



Welcome to *AeroAstro*, our annual publication about the MIT Department of Aeronautics and Astronautics and our community.

This past February, Ian Waitz, our department head of the last three years, was named Dean of the MIT School of Engineering. An honor, indeed, for our department, but, more importantly, an excellent new head for the school—in Provost Rafael Reif’s words, Ian is “an innovative thinker, a gifted teacher, and an effective leader.”

On behalf of all in AeroAstro, we thank Ian for his outstanding tenure as head and the wise council he provided to our faculty, students, and staff. We also offer our gratitude to Dave Darmofal who so ably handled both the role of associate department head and then interim head, and for the tremendous effort he placed on developing our academic programs and initiatives. And, our thanks to Eytan Modiano for his assuming the time consuming and demanding role of interim associate head during the transition. AeroAstro continues to be one of the world’s premier centers for aerospace education and research, thanks to these individuals, and to the efforts and talents of our remarkable faculty, staff, students, alumni, and friends.

On July 1, it was our great honor to become head and associate head of this historic department. We’ll carry on with many of the important initiatives Ian and Dave fostered. We’re looking at renovating additional parts of our facilities, bolstering our ever-widening collaboration with industry, and



involving more of our esteemed alumni in our activities. We’ll also be exploring new initiatives of which you will learn in coming months.

The same day we became department head and associate head, it was our great pleasure to welcome two new faculty members: Julie Shah and Kerri Cahoy. Julie’s expertise is in robotics and in human robot-collaboration. Kerri’s is in space exploration and in the study of the atmospheres and ionospheres of the solar system. The addition of these two talented and respected women further enhances AeroAstro’s outstanding abilities in two vital areas of contemporary research.

While our community brings together individuals with different backgrounds, we all share a commitment to aerospace education and research. One of our main strengths is our culture of establishing internal and external collaborations that, time and time again, have enabled us to address the most challenging problems. In this issue of our department annual review, AeroAstro, we share with you our research in on autonomy and humans-in-the-loop systems, vital aerospace growth areas connecting the work of a number of our faculty and labs. A special thanks to Professor Jonathan How for coordinating the contributions of these articles.

In addition to this work, there many other fascinating activities going on in AeroAstro—you can read about them here in the Lab Report section, on our website <http://www.mit.aero>, or better still, though a visit to the department.

As we approach 2014 and the 100th anniversary of the birth of MIT aeronautical education, we are both humbled and excited to don the mantles of AeroAstro leadership and to continue a century of unwavering commitment to educational excellence and advancing aerospace research. We welcome the thoughts, ideas, and help from all members of our great, extended AeroAstro community. Let’s hear from you.

Jaime Peraire,
Department Head

Karen Willcox,
Associate Head

FACULTY INTERVIEW
Flying the Left Seat: New AeroAstro Head Jaime Peraire Takes the Controls
By William T.G. Litant

1

AEROASTRO SPECIAL ISSUE
Autonomous & Humans-in-the-Loop Vehicle Systems Research
By Jonathan P. How, Emilio Frazzoli, and Brian Williams

6

THINKING FOR THEMSELVES
Autonomous Robots Plan Their Own Actions in Complex, Dynamic Environments
By Jonathan P. How, Emilio Frazzoli, and Brian Williams

8

HUMANS-IN-THE-LOOP
Human-Automation Collaboration Presents Possibilities Unattainable by Either Alone
By Mary “Missy” Cummings, Jonathan P. How, and Brian Williams

16

WHERE AM I?
Absent External Positioning Systems, UAVs Need to be Clever Learners
By Nicholas Roy and Jonathan P. How

22

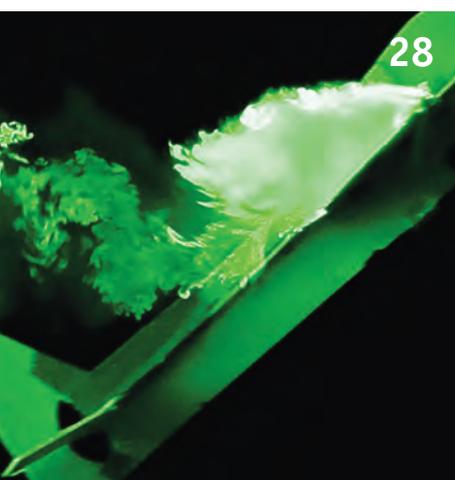


AUTONOMOUS MOBILITY 28
Novel Tools and Routing Algorithms' Impacts Range from Daily Commutes to Space Travel
By Emilio Frazzoli, Jonathan P. How, Nicholas Roy, Russ Tedrake, and Brian Williams

MIT AUTONOMOUS SYSTEMS EDUCATION 36
Training the Next Generation
By Brian Williams

ALUMNI INTERVIEW 44
You Don't Need a Pilot When You Have Dave Vos
By Richard Dahl

LAB REPORT 48
A 2010-11 Review of Aeronautics and Astronautics Department Laboratories



A close-up portrait of Jaime Peraire, a middle-aged man with grey hair and a goatee, wearing black-rimmed glasses and a blue and white vertically striped button-down shirt. He is resting his chin on his right hand, looking thoughtfully at the camera. The background is a blurred office setting with a wooden desk and stacks of papers and books.

FACULTY INTERVIEW

FLYING THE LEFT SEAT

New AeroAstro head Jaime Peraire
takes the controls

By William T.G. Litant

On July 1, 2011, Jaime Peraire, the H. N. Slater Professor of Aeronautics and Astronautics, became the 13th head of the MIT Department of Aeronautics and Astronautics, succeeding Ian Waitz, who is now dean of the School of Engineering.

“[Peraire] is internationally known for his scholarship in computational fluid mechanics, computational mechanics, and numerical simulation methods,” Waitz emailed the AeroAstro community. “He is also an exceptional colleague and dedicated teacher ... the department will be in very good hands.”

Peraire joined MIT in 1993 as an associate professor after earning undergraduate and graduate engineering degrees from the University of Barcelona in 1983 and 1987, his Ph.D from the University of Wales in 1986, and his D.Sc. from the University of Barcelona in 1987. Before joining MIT he was on the faculty at the University of Wales in Swansea, and at the Imperial College of Science Technology and Medicine in London. He was named a full professor in 1999. One of his major projects at MIT was co-creating the Computation for Design and Optimization master’s degree program.

Prior to taking the AeroAstro helm, Peraire directed the Aerospace Computational Design Lab, which researches application of computational engineering for aerospace system design and optimization. His research interests include computational aerodynamics, and simulation-based design and numerical analysis. His work has applications in computational compressible-fluid dynamics and other multidisciplinary aeronautics prob-

lems. Software products based on Peraire’s research, such as the FELISA suite of codes for re-entry aerodynamics, have been used throughout the aerospace industry.

Peraire is a former chairman of the MIT Faculty Committee on Undergraduate Admissions and Financial Aid. He is also a director of MIT International Science and Technology Initiatives’ Spain Program, which connects MIT students to professional internships and research with leading Spanish companies, universities and research institutes. He is an International Association in Computational Mechanics fellow and a University of Wales honorary professor.

Peraire has three sons, ages 15, 14, and 11. His wife, Anna Bueno, teaches Spanish in the Bedford, Mass. public schools and collaborates with Massachusetts Advocates for Children.

AeroAstro sat down with Professor Peraire in July to ask him for some early thoughts on directions and plans for the department.

AeroAstro: What were your first thoughts when you became department head?

Peraire: That this is truly a remarkable department. This is a very exciting job, but it also carries a lot of responsibility. The first thing I wanted to do was to meet with our faculty and staff and learn in more detail what they do. I’ve already spoken to most of them, and I’ve visited most of the department labs. We’re doing very good work and we are meeting great challenges both in education and research.

**THIS IS TRULY
A REMARKABLE
DEPARTMENT.**

AeroAstro: What challenges do you see for the department?

Peraire: Our main challenge is to remain a world premier institution for aerospace education and research. We have many strengths. For example, on the aeronautics side, we have great expertise in understanding air transportation's environmental impacts and on the design of novel, more efficient and capable aircrafts. We also have a strong activity on autonomous aircrafts and on integrating these aircraft into larger systems that involve humans in a supervisory role. On the space side, we're strong on manned and unmanned exploration, and also on robotics, and space systems. We have faculty whose expertise spans multiple areas, and we've been hiring new faculty with multidisciplinary skills. All these multitalented people are networking and connecting.

Let me tell you a little about my view of the department. What really makes us strong and effective is our ability to collaborate and work together and to mobilize for large projects that no single person would be able to do because of the breadth. In fact, some of the most exciting projects in the department don't involve just one or two faculty or research scientists, but four, five, or even more.

AeroAstro: Can you give us a couple of examples?

Peraire: A good example of research involving multiple AeroAstro faculty is the Deck Operations Course of Action Planner project, a decision support system for planning vehicle and aircraft movement on carrier decks and on approach. AeroAstro professors Missy Cummings, Emilio Frazzoli, Jon How, Nick

Roy, and Randy Davis are all contributing their expertise in different areas of human/machine interaction and automation to this project. Another example is the N+3 project we're doing for NASA, designing a green commercial aircraft that could use 70 percent less fuel than current planes, and reducing noise and nitrogen oxide emissions. Professors and researchers Edward Greitzer, Mark Drela, John Hansman, Jack Kerrebrock, Bob Liebeck, Zolt Spakovsky, Choon Tan, Jim Hileman, and Elena de La Rosa Blanco are working on a variety of areas: airframe design, gas turbine design, emissions mitigation.

There are also several other examples in areas such as environmental impact, air traffic management, and autonomous vehicles.

The opportunity areas are always changing. In some areas that have been active in the past, we will very likely see a decreased activity. I also see new challenges and, therefore, the need for new ideas and new research. One challenge will be managing the national and international air transportation system, which is nearing capacity. This is a system that has a tremendous economic impact—how are we going to address that? Related to this is the issue of aviation impact on climate, pollution, and noise. Those are issues in the civil area. In the military area, it's autonomous vehicles. The number of UAVs is going to grow, and with that will come the complexities of autonomous flying and coordination among vehicles. In space, the future of manned spacecraft is unclear, but there are certainly important opportunities for robotics as well as great potential for new types of space propulsion.

There is very exciting research in materials science, and new materials are being developed that will enable many of the above systems to be built.

And, of course, there is the area of computational modeling. This is an area close to my research. Nowadays we can simulate and optimize complex processes that in the past, we had to design based on common sense, or using simplistic rules. For example, it is conceivable to build a model for an aircraft such that if we make some changes to the geometry, we'll know the impact on the materials and on the propulsion, but also on the noise and how noise regulations will govern or constrain what we're doing. In some cases, we can incorporate and quantify uncertainty in our models. So you can make these very realistic macro models to support the decision-making process and give you a complete picture of what you're doing.

AeroAstro: Some are saying that with the Shuttle program over and uncertainly about the future of human space exploration, this might negatively affect the number of students interested in aerospace careers. Does that concern you?

Peraire: Well, it will pose a challenge. Clearly, interest in some areas will be reduced, but there are always new opportunities. I am confident that we will flourish. It's also important to emphasize that the education we offer doesn't limit students to work in a specific area; they have very broad choices. We provide our students a well-rounded education. In addition to our formal subjects, students learn written and oral communication skills, teamwork, the economic and political context in which we engineer, and



professional responsibility. We have alumni in management, telecommunications, teaching, research, military service, and many other technology-intensive fields. They all say their AeroAstro education helped them in ways they never imagined it would.

AeroAstro: What other areas are of importance to you and the department?

Peraire: Another area is our relationship with industry and outside labs like Draper and Lincoln. Over the past few years we've made great strides in this area, reconfirming long-standing relationships with industry and forging new ones. The benefits of these relationships are huge: these companies and labs are partners in research, participate in our capstone projects, contribute components and materials, provide fellowships and summer internships, and recruit our students. When our students end up working for them, the feedback and praise we get from industry is overwhelming.

And, I want to say something about our undergraduate program. Regardless of the future of the aerospace enterprise, which I think is bright, there will be plenty of opportunities for our students. There will be some changes we'll probably make to our curriculum in coming years—nothing major, but we're always looking at ways to improve. For example, our new 16-ENG flexible engineering degree. It offers increased flexibility for the students to focus in the areas of study they are passionate about and which are relevant for many of the current challenges. In some cases, students may choose to

gain a deeper knowledge on a specific area such as energy, transportation, or environment, or choose a multidisciplinary program combining disciplines in a manner not previously possible.

AeroAstro: You've said you have an interest in upgrading AeroAstro's physical plant. Can you elaborate?

Peraire: Yes. Many of our spaces are lagging behind those of some other leading schools and it's time to improve and modernize them. For example, take Building 31 (the Gas Turbine Lab). It's 83 years old and needs extensive renovation. At one time, it was heavily invested in gas turbine technology research, but research opportunities and facility demands have changed. We have new labs focusing on robotics and autonomy. Our plan is to consolidate these labs in a modern lab and test facility that's conducive to faculty and student collaboration.

AeroAstro: Any other plans you'd care to mention?

Peraire: In 2007 we developed a comprehensive and forward-looking strategic plan for AeroAstro (<http://web.mit.edu/aeroastro/about/stratprt.html>). We'll be collecting data to see how closely we've followed that, and learn what we're actually doing. We'll hone our strategies, and then articulate our plans for faculty hires, resource development, and research collaboration. Also, we're going to start a seminar series called "New Trends in Aerospace." Twice a month, we'll hear outside experts in the field, as well as young researchers who may become potential faculty hires.

We're creating two new working committees. One is an ad-hoc committee on undergraduate programs to assess our programs and identify areas where we can improve the educational experience. A second permanent committee will be on space and resources management. The focus of this committee will be to develop a plan for better management and use of the departmental space, including teaching and lab space, and also improve the quality of the existing space.

AeroAstro: You've also mentioned an interest in the department's history.

Peraire: In three years we're going to celebrate a very important anniversary: the 100th anniversary of MIT's first aeronautical engineering class and, for all intents and purposes, the birth of this department. We have a rich history, with names like Doolittle, Draper, Hunsaker, Aldrin, Douglas, Seamans, Widnall, and research in areas like inertial navigation, and our many contributions to Apollo. Our history is so closely tied to the development of aerospace that I feel it is our responsibility to keep this information together and accessible to the general public as well as academics. We're thinking about video interviews with emeriti and alums, exhibits of artifacts and photos, and a special website where all this may be explored.

AeroAstro: Do you plan on continuing with your research while you head the department?

Peraire: Yes, very much. I'd like to do some teaching as well, although I probably won't be able to do that in my first year as head, but I'd like to at least fill in if needed because teaching is one of the things I'd miss the most. And, I will continue with my research group. (Laughing) But, ask me that again in a couple of years! →

OUR HISTORY IS SO CLOSELY TIED TO THE DEVELOPMENT OF AEROSPACE THAT I FEEL IT IS OUR RESPONSIBILITY TO KEEP THIS INFORMATION TOGETHER AND ACCESSIBLE TO THE GENERAL PUBLIC AS WELL AS ACADEMICS.



AEROASTRO SPECIAL ISSUE

AUTONOMOUS & HUMANS-IN-THE-LOOP VEHICLE SYSTEMS RESEARCH

In collaboration with Lincoln Laboratory, AeroAstro 16.82 (Flight Vehicle Engineering) and 16.885 (Aircraft Systems Engineering) students, under the direction of several faculty, staff, and teaching assistants, built two UAVs for the US Air Force to employ in ground based sensor system calibration. MIT Beaverworks, as the collaboration is called (in deference to the MIT mascot), is now developing an expendable micro UAV, to be deployed from a mother aircraft's anti-missile flare dispensers at altitude. (William Litant, MIT photo).

Autonomous systems are critical to both military and civilian aerospace applications. NASA relies on robotic missions for space exploration, while the military increasingly relies on unmanned ground vehicles and aircraft systems to execute missions. Flight hours for military Unmanned Aircraft Systems grew from about 1300 hours in 1991 to more than 160,000 in 2006 (and 400,000 in 2009). The rapid expansion of military UASs like the Predator and Global Hawk has also increased the levels of interest in civilian UAV applications related to disaster and emergency response.

A key feature characterizing the evolution of these systems is the increasing level of autonomy. Challenges exist not only in achieving higher levels of autonomy, but also in integrating autonomous operations into systems, and in determining the most effective role for humans. For example, how can we integrate thousands of autonomous flying vehicles—to be used for homeland security, or emergency response—with the 5000 commercial passenger aircraft in the air over the United States on any given day?

AeroAstro faculty collaborate to address a variety of issues pertaining to autonomous systems, including control and estimation, artificial intelligence, human supervisory control, micro and nano air vehicle design, distributed path planning and task allocation, and communication networks for teams of autonomous vehicles.

Excerpted from "Our Future: AeroAstro Strategic Report 2007"

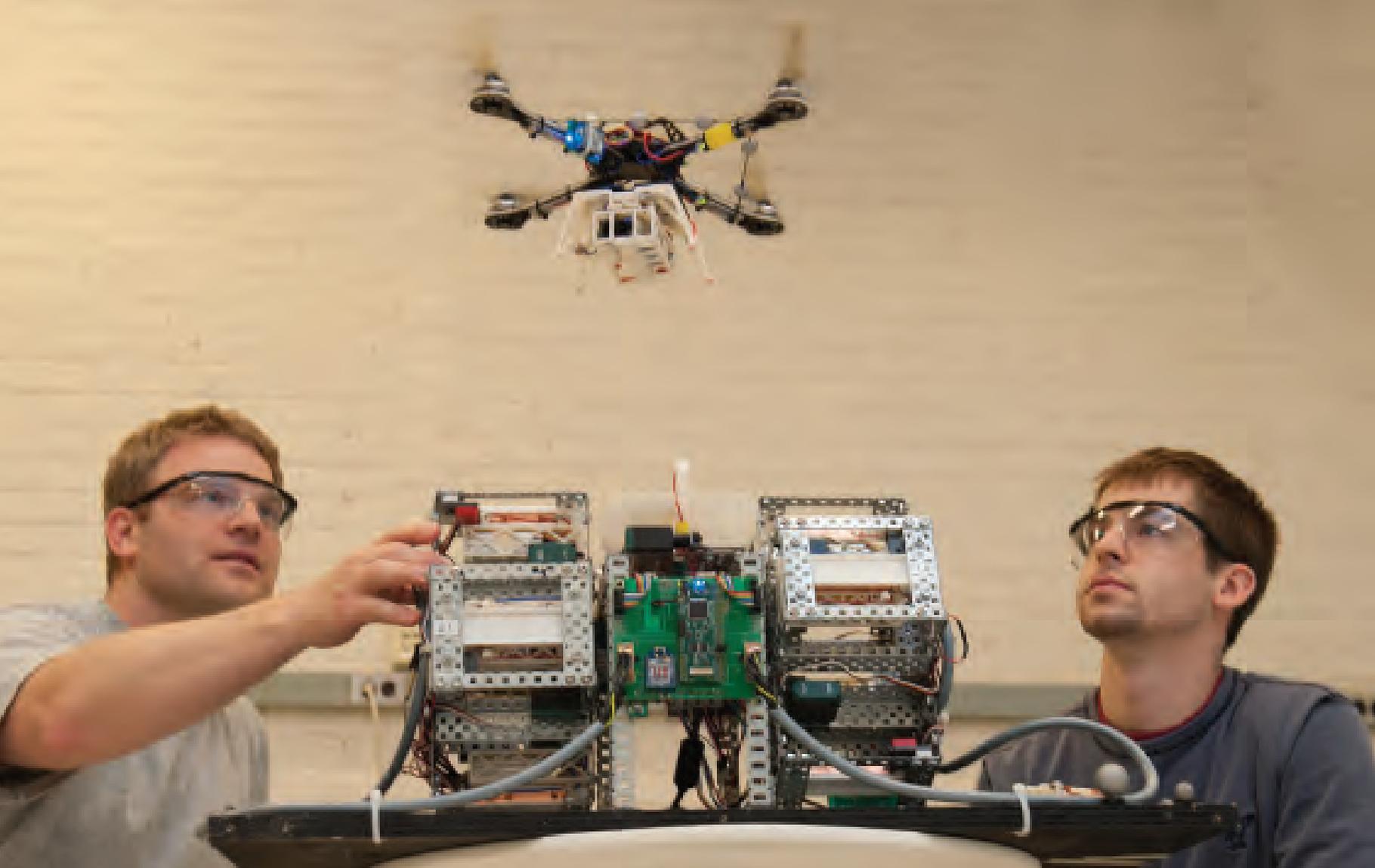
In the four years since the Aeronautics and Astronautics Department's most recent strategic report was produced, civilian and military applications, and uses for autonomous and real-time humans-in-the-loop systems have grown by astronomical proportions. This special *AeroAstro* issue highlights many of the innovative solutions being investigated within the Department to expand and mature these system's capabilities. Our research is addressing the challenges associated with autonomous unmanned aircraft and ground vehicles (UxVs), as well as developing algorithms to enable synergistic collaborations between human operators and (semi-) autonomous planners. The work reported has already had an important impact on the military, and will continue to do so with the planned future increase in UxV use. We anticipate that the technologies will also begin to play an even more significant role in emergency response and disaster relief, agricultural mapping, and manufacturing, especially with the president's recently announced National Robotics Initiative: \$70 million for "the development and use of robots in the United States that work beside, or cooperatively with, people." To keep abreast of our activities in this realm, I invite you to visit the web pages of the labs that are conducting this research:

- » Aerospace Control Laboratory <http://acl.mit.edu/>
- » Aerospace Robotics and Embedded Systems <http://ares.lids.mit.edu/>
- » Humans and Automation Laboratory <http://halab.mit.edu/>
- » Laboratory for Information and Decision Systems <http://lids.mit.edu/>
- » Model-based Embedded & Robotic Systems
<http://groups.csail.mit.edu/mers/mers.htm>
- » Robust Robotics Group <http://groups.csail.mit.edu/rrg/> ➔

JONATHAN P. HOW

Richard Cockburn Maclaurin Professor of Aeronautics and Astronautics
Director, Aerospace Controls Laboratory

Guest editor, *AeroAstro* featured section on autonomous/humans-in-the-loop systems



Aerospace Controls Lab Ph.D. students Josh Redding (left) and Buddy Michini monitor an autonomous quadrotor positioning itself to land on a battery recharge station. As soon as it perches on the landing platform (just above the green circuit board in the center) a fresh battery will slide into the vehicle from the rotating carousel on the right, the drained battery will slide into the carousel on the left for recharging, and the vehicle will take off to continue its mission. The system enables long duration surveillance missions with minimal human support. (William Litant/MIT photo)

THINKING FOR THEMSELVES: Autonomous robots plan their own actions in complex, dynamic environments

By Jonathan P. How, Emilio Frazzoli, and Brian Williams

Automation has the potential to greatly improve the performance and capabilities of future robotic vehicles, such as cars and airplanes.

The reader might be familiar with autonomous vehicles, such as the Roomba vacuum cleaning robot, that perform fairly simple tasks in constrained environments—but the goals of this work are to develop much smarter robots that can operate in, and adapt to, the dynamic and complex world familiar to humans. This includes examples such as an autonomous car that optimizes its route to a pick-up point to avoid traffic tie-ups reported by other vehicles, while designing motion paths that avoid potentially erratic maneuvers by pedestrians, cyclists, and other cars. It could also include a team of UAVs collaborating to choose the best locations to sample the atmosphere to better predict a storm's path.

From choosing which actions to take, to deciding which maneuvers to execute to perform those actions, planning is a crucial part of optimizing the solution to the fundamental questions of “what, where, when, how?” Of course, to operate in a dynamic world, this planning must be fast enough that it can be performed online, in real-time. The result is similar to classical feedback control, in which sensors provide information about the motion of the system, and then use the information to compute corrective inputs. But, autonomy extends that framework to include both continuous and discrete decisions, such as activity planning, compliance to rules of behavior, and trajectory design.

There are numerous challenges to achieving these goals, such as developing planning algorithms that are both computationally tractable and communication-efficient, adapting the autonomous

systems to interact in a synergistic and trustworthy fashion with human operators, and handling uncertainty in the location, motion, and intent of other objects.

The research groups led by MIT Aeronautics and Astronautics Professors Emilio Frazzoli, Jonathan P. How, and Brian Williams have developed several new approaches to address the computational complexity challenges inherent in both trajectory design and activity planning.

TRAJECTORY PLANNING

Trajectory planning in an environment with constrained dynamics and obstacles is a complex problem, even for guiding a single vehicle. Numerous approximate solutions have been developed over the years using a variety of different strategies. One approach, called sampling-based planning, is particularly attractive because it scales well with the problem size and provides a systematic method of exploring the environment for a feasible path, while, at the same time, refining any path to the goal that may have been found. Key amongst these algorithms is the Rapidly-Exploring Random Tree (RRT) that has proven to be a successful approach for designing safe trajectories for autonomous systems.

MIT DARPA Urban Challenge team members How and Frazzoli built on this success to develop the Closed-loop Rapidly-Exploring Random Tree (CL-RRT) algorithm to address the challenges of planning paths for an autonomous car with unstable and nonlinear dynamics. The algorithm was successfully demonstrated at the 2007 DARPA Urban Challenge, which was held from October 26 through November 3rd in Victorville, Calif. MIT developed a unique autonomous vehicle: Talos, a Land Rover LR3 equipped with a diverse range of lidar, vision, radar, and navigation sensors connected to a powerful blade cluster computer system. The MIT vehicle employed novel algorithmic approaches to perception, planning, and control for the challenging task of autonomous driving in uncertain, dynamic environments. The vehicle was one of 35 that participated in the DARPA Urban Challenge National Qualifying Event, and, based on our performance there, was one of 11 teams to qualify for the Urban Challenge Event based on our performance. The vehicle was one of only six teams to complete the race, finishing in fourth place.

Through the addition of a path-tracking control loop in the system's RRT prediction model, CL-RRT has achieved accurate tracking of predicted trajectories. This feedback control loop also enables a more efficient RRT sampling strategy, so that a single input to the closed-loop system can create a long, dynamically feasible, trajectory (on the order of several seconds) while the controller provides a high-rate stabilizing feedback to the vehicle.

While RRTs are effective and versatile, they provide no performance guarantees. In fact, recent work has shown that they are guaranteed *not* to converge to the best path. However, members of the Aerospace Robotics and Embedded Systems Laboratory, led by Frazzoli, have developed a modification to the standard RRT algorithm that ensures asymptotic optimality; that is, that the planner will find the best answer given sufficient time. The resulting RRT* algorithm shows that, under a number of technical assumptions, probabilistic convergence to the cost-optimal trajectory can be obtained.

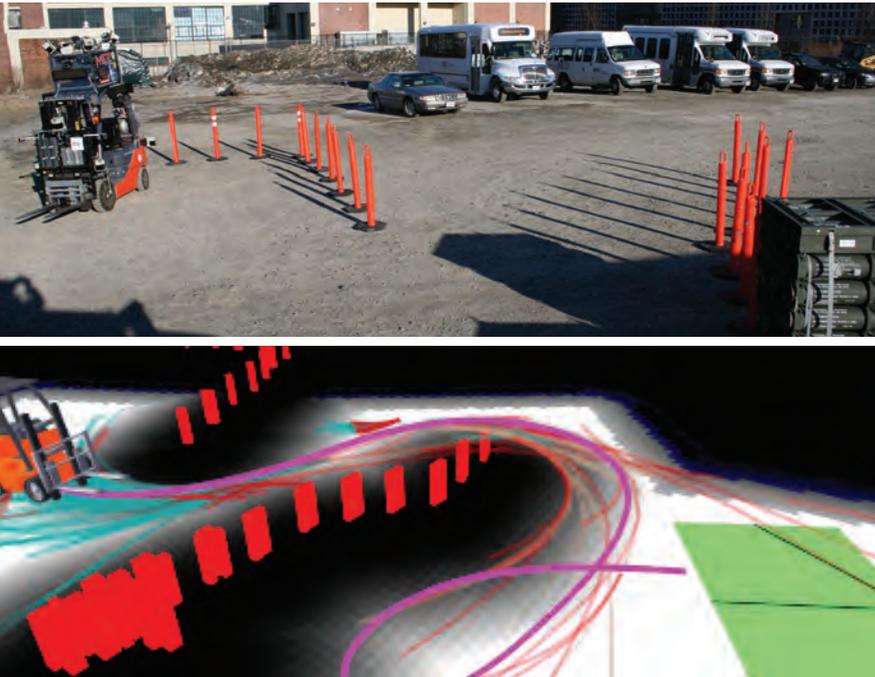
RRT* provides a systematic means of planning paths amongst static and/or predictably-moving obstacles, but planning safe paths around objects with poorly known or unpredictable paths poses a new set of challenges. Anyone who has driven through an intersection at night or in poor weather is familiar with the typical problems: Where are the lines or edge of the road? What are the expected paths of the other vehicles? Are they all good drivers? Do they know and obey the rules of the road?

To address the uncertainty in the vehicle path or the location of

Jonathan P. How and Emilio Frazzoli's novel algorithmic approaches to perception, planning, and control, used in conjunction with a range of lidar, vision, radar, and navigation sensors and a blade cluster computer system piloted this Land Rover to fourth place in the 2007 DARPA Urban Challenge. (Jonathan P. How/MIT photo)



obstacles, members of the Aerospace Controls Laboratory led by How developed the Chance-Constrained Rapidly-Exploring Random Tree (CC-RRT) algorithm. In addition to maintaining



In the photograph, the autonomous forklift navigates around cones and palletized cargo. The generated image depicts the activity as viewed by the autonomous planner, which identifies a tree of feasible paths and selects a safe trajectory (magenta) to maneuver around the perceived obstacle field (red, with black penalty regions) to reach the goal position (green).

the benefits of RRT algorithms, CC-RRT uses chance constraints to ensure that all constraints are satisfied with some minimum probability. This is known as “probabilistic feasibility.” In environments where absolute safety may be unrealistic, this allows the user to specify exactly how much risk is acceptable. The approach has been demonstrated to efficiently compute risk-aware trajectories for a variety of dynamics in complex, cluttered environments. The lab is now applying this approach to an autonomous parafoil to robustly avoid terrain in the presence of uncertain wind conditions.

Autonomous underwater vehicles (AUVs) are also being developed to enable long-term autonomous exploration of previously uncharted portions of the ocean, but performing these extended missions can be risky. For example, due to a sudden drift in current, an AUV can collide with a seamount if it moves too close to the sea floor while mapping a treacherous canyon. A seasoned

submarine commander would be skilled at identifying navigation paths that maximize scientific value, while operating within acceptable levels of risk. The Model-Based Embedded and Robotic Systems Research group led by Williams has developed robust, chance-constraint planning algorithms that automatically navigate vehicles to achieve user specified science goals, while operating within risk levels specified by the operator. These algorithms operate by iteratively allocating the user specified risk to different steps in the mission plan, until a risk allocation is found that maximizes science utility. This approach was used to navigate a vehicle to map portions of Monterey Bay during January 2008, and is currently being applied to the navigation of an autonomous personal air vehicle.

To handle uncertainty in the motions of other vehicles, ACL members developed a novel trajectory prediction approach that infers, in real-time, the intentions of the other agents in the environment, and embeds these in the calculations of the estimated reachability sets to obtain a probabilistic description of their future paths. Gaussian Processes provide an efficient means for encoding these intents, and the developed RRT-Reach algorithm efficiently computes the reachability sets, which are guaranteed to obey dynamic feasibility and avoid static obstacles. This greatly increases the accuracy of the prediction. The utility of the resulting RR-GP approach was demonstrated on the CC-RRT probabilistic planner by significantly increasing the safety of the planned paths in the presence of dynamic agents with uncertain intentions.

ACTIVITY PLANNING

Activity planning for multiple agents introduces many challenges. Typical problems involve a networked team of heterogeneous assets (manned/autonomous, air/ground, etc.) performing numerous tasks with temporal and logical constraints—and thus, there are many ways to accomplish mission goals. ARES developed techniques to formulate mission specifications in an expressive, yet natural, formal language such as Linear Temporal Logic (LTL). This includes Boolean operators (“and,” “or,” “not”), and temporal operators (“always,” “eventually,” “until,” “unless,” etc.), which are sufficiently expressive to capture many missions of interest. This work also led to a novel automated, systematic procedure to convert LTL specifications into a mathematical program, which enables an efficient solution through COTS software. ARES has also developed an RRT-like sampling-based algorithm, called RRG, to compute trajectories that are feasible with respect to a language called $m\mu$ -calculus, which is strictly more expressive than LTL.

ACL developed a novel distributed task allocation planner (CBBA) with provable convergence and performance guarantees. CBBA builds on recent work associated with analyzing the flow of information in social networks (e.g., “gossip” algorithms), but focuses on agreement of plans rather than just information, which has proven to be more communication efficient for the planning problem. CBBA can handle time windows of task validity, time-varying networks, coordination constraints between agents to perform tasks, and asynchronous formulations that are better adapted for real-world implementation. These additions make CBBA a very general frame-

work that can be used to do predictive planning in real-time with nonlinear cost functions, and realistic vehicle dynamics for heterogeneous agents. CBBA has been experimentally tested using indoor flight facilities, and outdoor flight-testing will continue.

UNCERTAINTY

Uncertainty remains a ubiquitous feature of robotics applications and a key research challenge that potentially limits their deployment. There are, of course, many types of uncertainty, which can be roughly characterized as either internal (e.g., models) or external (e.g., wind). When the robots experience problems as a result of incorrect models or impact of disturbances, the agents can re-plan in light of new information. However, it is likely that the initial, incorrect decisions will have consumed resources (e.g., fuel, power), and may even have positioned agents in dangerous states where they are unable to respond effectively to the new information. Thus, in constructing their initial plan, the agents should hedge against their uncertainty, and select robust plans that “expect the unexpected.”

A key challenge here is that embedding the models required to accurately predict the stochastic environment typically leads to computationally intractable planning problems. This suggests the use of simplified/abstracted models; however, this can lead to suboptimal (possibly catastrophic) performance. Furthermore, the parameters of these models are typically not well known, leading to additional uncertainty.

ACL developed computationally tractable techniques to improve the robustness (e.g., improve the worst case performance) of the planning algorithms. Recent success in this area includes Dirichlet Sigma Point Sampling, which provides a framework for reducing the number of scenarios required to accurately predict the worst-case performance. ACL is also pursuing a second approach that is similar to traditional adaptive control in that it has both direct (i.e., learns better plans to execute) and indirect (i.e., learns better estimates of the model to plan with) algorithms. Challenges in this case are that learning in large state spaces is slow, memory intensive, and computationally demanding.

**UNCERTAINTY REMAINS A
UBIQUITOUS FEATURE OF
ROBOTICS APPLICATIONS AND
A KEY RESEARCH CHALLENGE
THAT POTENTIALLY LIMITS
THEIR DEPLOYMENT.**

Recent successes here include incremental Feature Dependency Discovery (iFDD) and intelligent Cooperative Control Architecture (iCCA). The iCCA research has focused on developing algorithms to improve planner performance over time in the face of uncertainty and a dynamic world. Our approach augments the “safe” plans calculated by a standard planning module such as CBBA, and analyzes the past performance to incrementally adapt the policy to maximize future cumulative rewards. The integrated framework has been shown to boost solution optimality by an average of 10% in numerical trials, and ongoing work is investigating the performance improvements experimentally.

Learning methods often use a linear function approximation of the value function, a key component needed for the planner to determine the best actions to take. A classic challenge with function approximation techniques is how to select the set of basis functions with cheap computational complexity in large planning problems. Given an initial set of features, iFDD expands the set of basis in areas where approximation error persists. iFDD is simple to implement, fast to execute, and can be combined with any online learning technique. This technology allows for planning under uncertainty in real-life situations. For example, after an earthquake, a team of UAVs can commence a collaborative search and rescue mission in the disastrous area where the location and number of survivors are estimated based on satellite images.

The level of autonomy demanded of unmanned air, ground, and underwater vehicles by civilian and military operations is increasing steadily. The underlying algorithms must be able to operate effectively over long distances, for long durations, and with very little prior information. As one example of the future for autonomous systems, AeroAstro researchers are collaborating on a project to automate the operation of an aircraft carrier deck, developing novel algorithms for scheduling launch sequences, moving aircraft safely across the deck, and robust operation in rapidly changing and uncertain battle environments. These algorithms depend on theoretical advances in activity and trajectory planning and learning under uncertainty, which lie at the heart of the Department’s research in autonomy. We anticipate that these technologies will also play a critical role in developing the autonomous cars of the future. →



In the AeroAstro Humans and Automation Lab, Professor Missy Cummings and research assistant Jason Ryan work with the Deck operations Course of Action Planner, a virtual representation of aircraft carrier deck activity that, by partnering human and computer abilities, could greatly enhance planning tasks in a chaotic environment. (William Litant/MIT photo)

HUMANS-IN-THE-LOOP HUMAN-AUTOMATION COLLABORATION PRESENTS POSSIBILITIES UNATTAINABLE BY EITHER ALONE

By Mary “Missy” Cummings, Jonathan P. How, and Brian Williams

While we humans are capable of complex—even astounding—tasks and feats, we have known since the earliest days of mechanization that we can employ machines to extend human abilities, making it possible to do things faster and better.

Most people today are familiar with automated vehicles, such as aircraft drones, that require one or more people to control a single machine. But, in the future, we will see more and more systems where a small team, or even a single individual, oversees networks of a number of automated “agents.” In these cases

involving multiple vehicles traversing random, dynamic, time-pressured environments, the team or individual overseer is not humanly capable of the rapid and complex path planning and resource allocations required: they need automated planning assistance. However, such planning systems can be brittle and unable to respond to emergent events. Enter a human/machine planner partnership, known as “humans-in-the-loop,” where operators provide their human knowledge-based reasoning and experience to enhance the non-human planners’ abilities.

While numerous studies have examined the ability of underlying automation (in the form of planning and control algorithms) to control a network of heterogeneous unmanned vehicles (UxVs), a significant limitation of this work is a lack of investigation of critical human-automation collaboration issues. Researchers in AeroAstro’s Humans and Automation Laboratory (HAL), the Aerospace Controls Laboratory (ACL), and Model-based Embedded and Robotic Systems (MERS) are investigating these issues in several domains.

**THERE IS A SHARED SPACE
IN SUCH COMPLEX MISSIONS
FOR HUMAN-AUTOMATION
COLLABORATION.**

EXPEDITIONARY MISSIONS

ACL, HAL, and Aurora Flight Sciences have developed the Onboard Planning System for UxVs Supporting Expeditionary Reconnaissance and Surveillance (OPS-USERS), which provides a planning framework for a team of autonomous agents, under human supervisory control, participating in expeditionary missions that rely heavily on intelligence, surveillance, and reconnaissance. The mission environment contains an unknown number of mobile targets, each of which may be friendly, hostile, or unknown. The mission scenario

is multi-objective, and includes finding as many targets as possible, keeping accurate position estimates of unknown and hostile targets, and neutralizing the latter. It is assumed that static features in the environment, such as terrain type, are known, but dynamic features, such as target locations, are not.

Given a decentralized task planner and a goal-based operator interface for a network of unmanned vehicles in a search, track, and neutralize mission, this research demonstrated that humans guiding these decentralized planners improved system performance by up to 50 percent. However, those tasks that required precise and rapid calculations were not significantly improved with human aid. Thus, there is a shared space in such complex missions for human-automation collaboration.

AIRCRAFT CARRIER DECK OPERATIONS

A second application domain for humans-in-the loop collaboration involves the complex world of aircraft carrier deck operations. Into this already chaotic environment of human-piloted airplanes, helicopters, support vehicles, and crew members, the military is now introducing Unmanned Aerial Vehicles, further complicating the choreography in a field of restricted real estate. Currently, deck operation planning tasks are performed by human operators using relatively primitive support tools. In fact, a primary tool, colloquially known

as the “Ouija Board,” involves pushing tiny model planes around a table on which a scaled deck is outlined. Due to the expertise of key human decision-making skills, this approach works, but is sometimes inefficient. Given the desire to improve and streamline operations that will involve UAVs, decision makers need real-time decision support to manage the vast and dynamic variables in this complex resource allocation problem.



The Deck operations Course of Action Planner (DCAP) project, a collaboration among AeroAstro professors Cummings, How, Roy, Frazzoli and their students, and Randy Davis of EECS/CSAIL, is a decision support system for aircraft carrier contingency planning. DCAP is a collaborative system, using both a human operator and automated planning algorithms in the creation of new operating schedules for manned and unmanned vehicles on the carrier deck and in the air approaching the carrier. To facilitate operator situational awareness and communication between an operator and the automation, a visual decision support system has been created consisting of a virtual deck, people, and vehicles projected on a table-top display. DCAP allows human decision makers to guide the automated planners in developing schedules. The system supports a range of operator decision heuristics, which work well when carrier operations are straightforward with few contingencies to manage. However, when multiple failures occur and the overall system, both in the air and on the deck, is stressed due to unexpected problems such as catapult failures, overall performance is enhanced by allowing the automation to aid the operator in monitoring for safety violations and making critical decisions.

More than a decade into the 21st century, aircraft carrier handlers' primary tool, the “Ouija Board,” consists of tiny model planes that they push around a table. It works, but performance is limited. (US Navy photo)

PERSONAL AIR VEHICLES

Personal air vehicles are a vision of aviation's future popularized in the early 1960s when George Jetson packed his family and dog into his famous clear-domed car and, at the push of a button, took to the skies over Orbit City. After decades of less-than-successful plans and prototypes, companies like the MIT spin-off Terrafugia are making this vision a reality by offering vehicles that can both fly through the air and drive down the road. To fly these vehicles, one must be a certified pilot, thus limiting the population that can benefit from this innovative concept.

The MERS group has demonstrated in simulation the concept of an autonomous personal air vehicle, called PT, in which passengers interact with the vehicle in the same manner that they interact today with a taxi driver. To interact with PT, passengers speak their goals and constraints; for example, "PT, I would like to go to Hanscom Field now, and we need to arrive

by 4:30. Oh, and we'd like to fly over Yarmouth, if that's possible. The Constitution is sailing today." PT checks the weather, plans a safe route, and identifies alternative landing sites, in case an emergency landing is required. In the event that the passenger's goals can no longer be achieved, PT presents alternatives. PT might say, "A thunderstorm has appeared along the route to Hanscom. I would like to re-route to avoid the thunderstorm. This will not provide enough time to fly over Yarmouth and still arrive at Hanscom by 4:30. Would you like to arrive later, at 5, or skip flying over Yarmouth?" In the future, PT will be able to reason about user preference, and will be able to ask the user probing questions that will help her identify the best options.

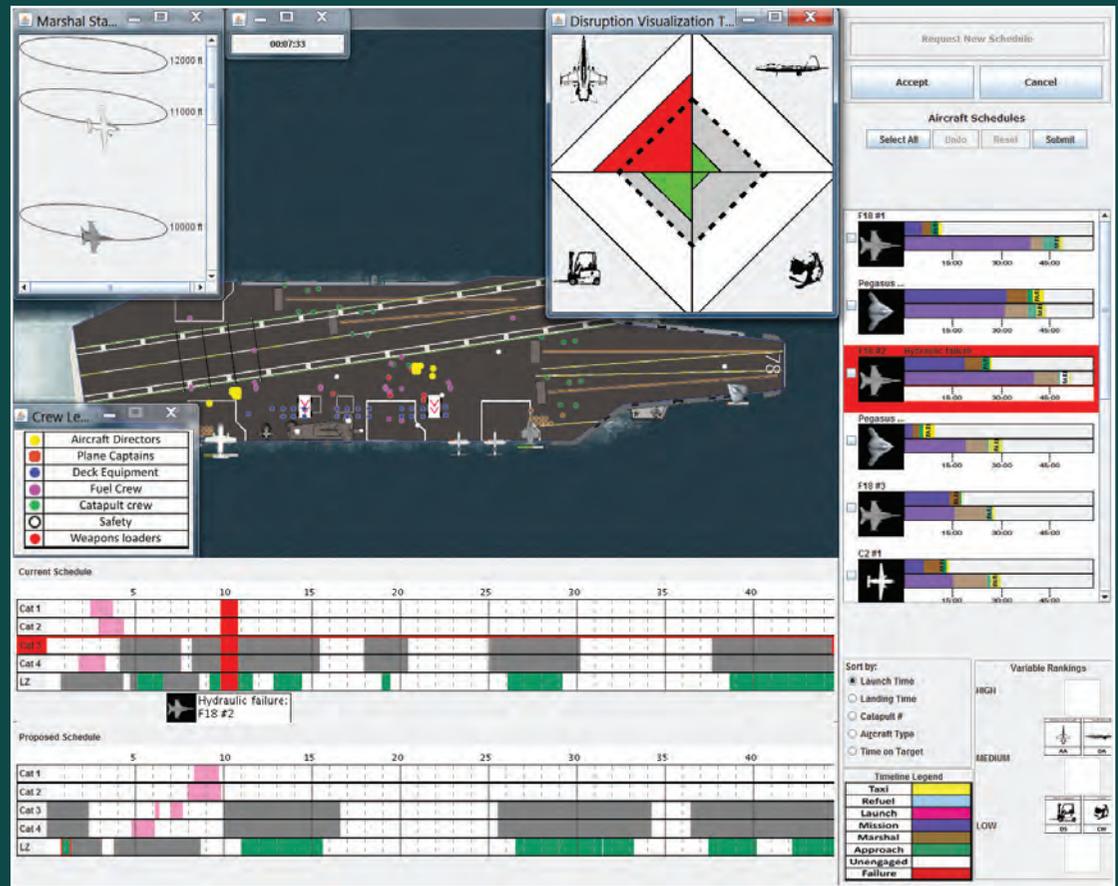


Transition, an airplane that doubles as a car, is an example of a Personal Air Vehicle that could benefit from advanced human/computer interaction. Now in preproduction, its designers conceived of the vehicle while they were AeroAstro grad students. (Terrafugia photo)

A detailed look at the Deck operations Course of Action Planner as the aircraft carrier “handler” would see it. Here, the operator has submitted to the planning algorithm priority rankings for four personnel groups, and desired schedules and priorities for individual aircraft.

On the bottom edge of the image we see a pair of Deck Resource Timelines. Each of these contains five timelines showing the allocation of tasks to the four launch catapults and the landing strip. The upper half shows the current resource allocations; the bottom half shows the proposed allocation. This allows the user to quickly identify what changes have been made in the schedules.

This convention is also used on the right-hand side of the screen in the Aircraft Schedule Panel. The ASP shows individual timelines of operation for all aircraft in the system. For each aircraft, we again show two timelines stacked on top of one another, and again, the current is on top, with the proposal on bottom. This allows users to make a quick visual pass over the data and review how the planner is suggesting the schedules be changed—or how changes in the dynamics of the system, due to failures or delays, have affected schedules.



Another important item is the multicolored diamond in the upper right area of the screen. This is the Disruption Visualization Tool, which displays relative changes in personnel group workload between the current and proposed schedules. Smaller, green triangles imply that this group will take less time to perform its task assignments in the proposed schedule. Larger, red triangles imply that more time is required. Note that, at this

time, the DVT shows workload as it is the main criterion that the scheduling algorithm optimizes. The planner attempts to minimize both overall mission duration (time to complete all tasks) and minimize the workload of individual personnel groups. →



Students (from left) James Wiken (standing), Abraham Bachrach, Samuel Prentice, and Adam Bry prep a pair of quadrotor helicopters to fly through MIT's Stata Center, exploring and mapping the building. Equipped with a variety of sensors for operating in different environments, the rotorcraft can fly in complex, populated environments. (William Litant/MIT photo)

WHERE AM I?

Absent external positioning systems, UAVs need to be clever learners

By Nicholas Roy and Jonathan P. How

Autonomous unmanned aerial vehicles are increasingly a part of military and civilian flight operations. Examples range from surveillance over Iraq and Afghanistan, to critical use in monitoring the Fukushima nuclear reactor and disaster relief coordination in response to the Haitian earthquake.

UAV guidance and control has traditionally depended on both an external positioning signal such as GPS for position information, and an existing map for planning flight paths. This dependence has restricted UAVs to applications where the vehicle can operate at altitude, ensuring good GPS signals and few obstacles.

OPERATIONAL CHALLENGES INCREASING

Operational requirements for UAVs, especially micro aerial vehicles (MAVs), are expanding to include flight at low altitude in complex, populated environments. Search and rescue, surveillance, and other tasks may require MAVs to reliably fly through the “urban canyon” and enter buildings. However, most indoor environments and many parts of urban environments remain without access to external positioning systems such as GPS, thus limiting autonomous MAVs’ ability to fly through these areas.

To overcome the absence of external position systems, onboard sensors have been used successfully for navigation in a number of autonomous vehicle applications. For operation in unknown environments, these sensors allow a robot to explore the environment, collect sensor data, such as camera images or data from a ranging sensor, and use statistical models to assemble the data into a globally consistent map of the world. Once enough data is collected

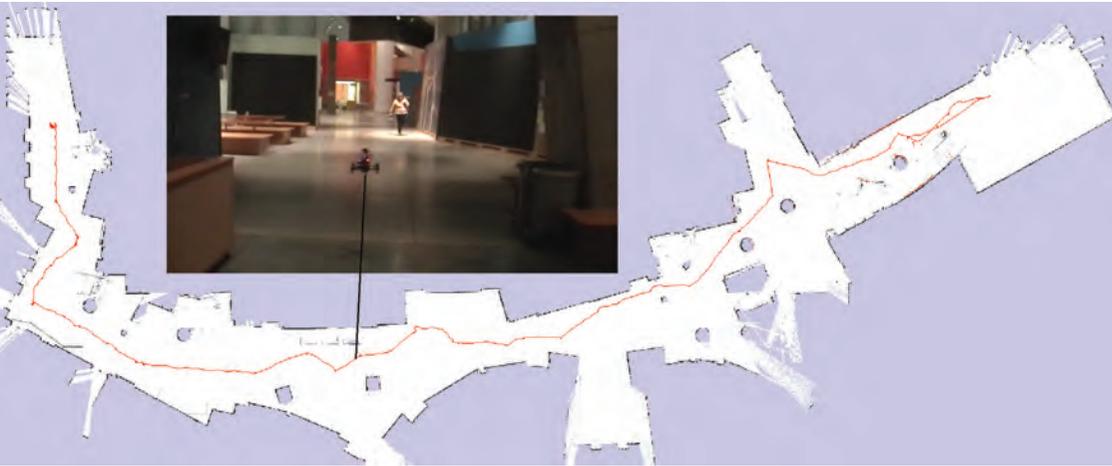
to generate a complete and precise map, the robot can use the map to choose collision-free trajectories, plan tasks, and make decisions.

The perception and estimation algorithms necessary for such GPS-denied navigation are now essentially off-the-shelf technologies for ground robots, but, until recently, using the same ideas to allow UAVs and MAVs to navigate through unknown environments using onboard sensors has been an open research challenge. The air vehicles' fast dynamics require not only rapid position estimation, but also fast and accurate velocity estimation. Additionally, unlike ground vehicles, air vehicles cannot simply stop and perform more sensing when their state estimates contain large uncertainties. The Robust Robotics Group (RRG) in the MIT

Computer Science and Artificial Intelligence Laboratory develops inference, planning, and learning algorithms for unmanned vehicles to address these challenges.

The RRG has developed state estimation algorithms that allow UAVs and MAVs to exploit structure in sensor data to infer both position and velocity accurately and quickly, an order of magnitude faster than the state

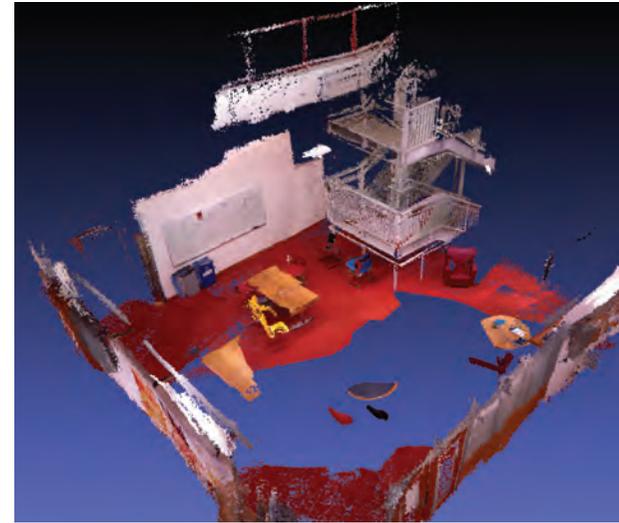
of the art in ground vehicles. These algorithms can be used both to estimate the vehicle's state in the world and simultaneously to build a model of the world. Using a lightweight laser rangefinder, the group demonstrated that a quadrotor helicopter can enter a building under autonomous control, explore the building searching for target objects (e.g., a control panel), and construct a map of the building to be transmitted to first-responders, enabling them to



A first floor map of MIT's Stata Center constructed by a UAV during autonomous flight. The vehicle's trajectory is shown in red.

safely enter the structure. An example map built by an autonomous quadrotor depicting MIT's Stata Center is shown on the previous page.

While the laser rangefinders used to build this map are highly accurate, they provide only a limited perception of the world, typically in two dimensions. In contrast, recent improvements in RGB-D cameras have provided a path to rich 3D perception of the environment. Additionally, commodity RGB-D cameras such as the Microsoft Kinect are becoming both lightweight and low-cost. RGB-D cameras illuminate a scene with a structured light pattern, and examine and compare light pattern changes with changes in scene depth to recover the distance to each image pixel. This technique is similar to stereo imaging, but differs in the range and spatial density of depth data, allowing the RGB-D camera to estimate depth even in areas with little visual texture.



A 3D map of an MIT lab space multi-story environment generated using a Microsoft Kinect during an autonomous quadrotor flight. The Kinect was originally developed to enable interaction with the Xbox 360 by using gestures, obviating the need touch a controller.

ACTING RELIABLY WITH IMPERFECT DATA

Even with the recent progress of perception algorithms that allow vehicles to sense and learn about their environment, the real world is impossible to sense completely and without error. All sensors, including laser rangefinders, conventional cameras, and RGB-D cameras, are limited in range and what can be sensed. If a vehicle does not take these limitations into account as it plans its motion, it can move out of range of the things it can sense, losing the abilities to detect obstacles, estimate its own position, or keep the vehicle safe and stable. The limitations on sensing, coupled with the dynamics and the degrees of freedom of the vehicle, create an acute need to integrate perception into the process of planning trajectories to ensure safe vehicle operation. Consequently, UAVs must be able to act reliably given imperfect, limited, and uncertain knowledge of the world by predicting how imperfect knowledge affects their performance, avoiding plans that could fail due to lack of information, and planning to learn more and improve their knowledge of the world.

The problem of incorporating sensor limitations and uncertainty into the planning problem is computationally challenging because the problem is fundamentally high dimensional. As



Nicholas Roy of the Robust Robotics Group is developing means for UAVs and micro aerial vehicles to accomplish complex tasks in complex environments. (William Litant/MIT photo)

a motion plan is constructed, not only must the state of the vehicle be predicted into the future; the possible sensor data and the effects on the vehicle state uncertainty must also be taken into account. Motion planning for high dimensional systems has traditionally been difficult, but MIT AeroAstro has considerable expertise in this area, with several research groups studying these challenges.

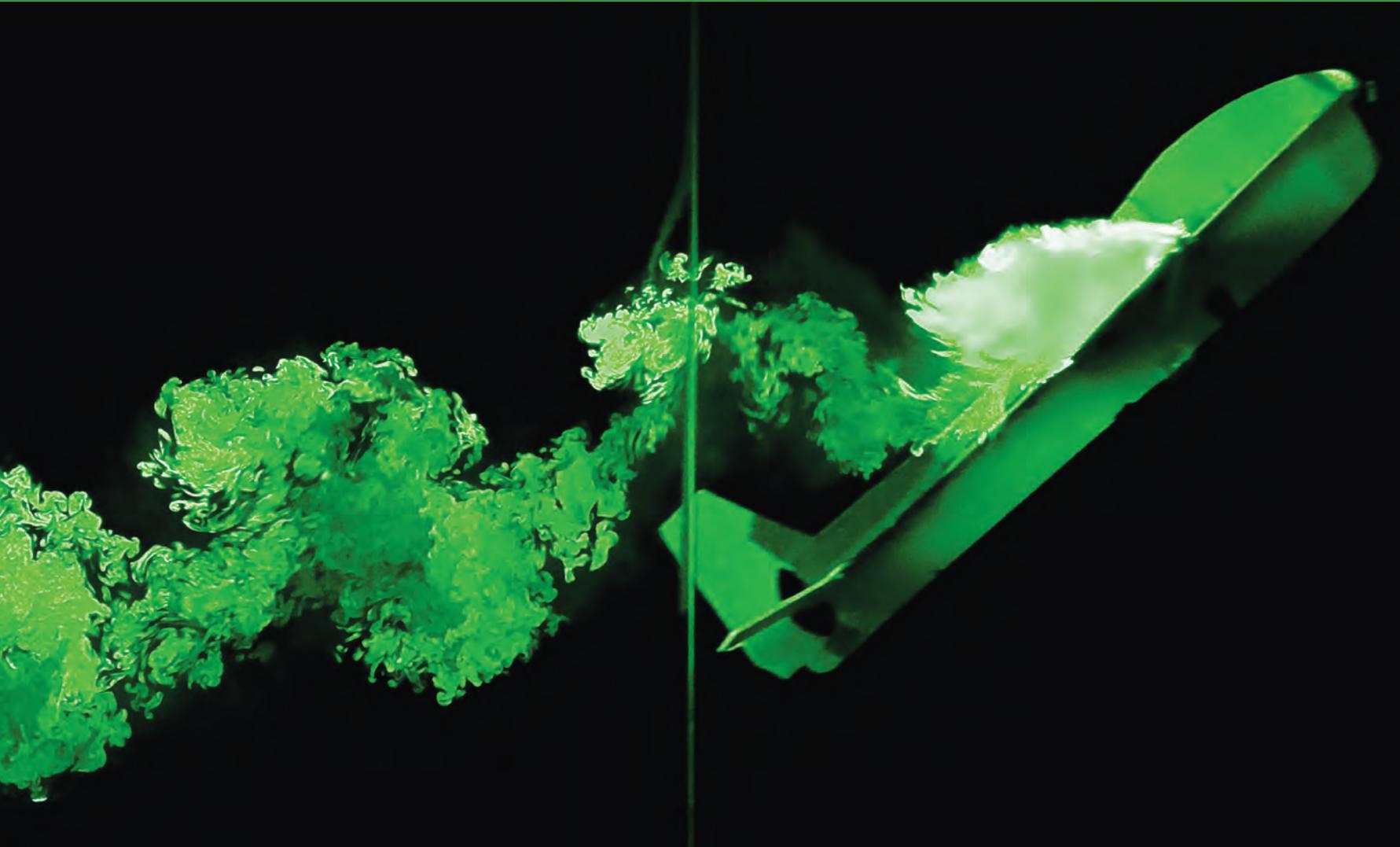
One recent success is motion planning that explicitly incorporates sensor limitations, such as a UAV navigating using a laser range finder with a limited range. In this setting, when the UAV cannot sense the local environment (e.g., is in the middle of a large room), the vehicle can become lost and the vehicle velocity estimate can begin to drift substantially, leading to high-speed collisions with the environment. By incorporating the uncertainty of the position estimate into the planning process using an algorithm known as the Belief Roadmap (BRM) algorithm, we can construct large trajectories in high-dimensional spaces as efficiently as conventional trajectory planners. The BRM algorithm allows a test helicopter to plan trajectories that keep the vehicle within range of a specific environmental structure at all times, and the UAV is able to fly reliably and autonomously in locations that are normally inaccessible to UAVs. The original formulation of the BRM assumed a very simple model of the dynamics of the vehicle. Even more recently, the RRG developed the Rapidly-exploring Random Belief Tree algorithm that can incorporate more complex vehicle dynamics, allowing researchers to extend the approach from quadrotor helicopters to fixed-wing vehicles operating safely in GPS-denied environments.

SENSING THE ENVIRONMENT

Another recent success addresses problems that focus more on sensing the environment, rather than the vehicle's own state estimate, planning trajectories for a vehicle carrying a sensor, attempting to collect the most information. There may exist resource costs associated with taking each measurement, leading to a tradeoff between the quality of information and the cost of obtaining it. The Information-rich Rapidly-exploring Random Tree (IRRT) algorithm, developed by the MIT Aerospace Controls Laboratory, offers a solution to this challenging motion planning problem. The planner embeds a notion of informativeness in conjunction with other metrics, such as distance traveled, time elapsed, or maximum risk, to identify lowest-cost paths in the tree over the course of the mission. In a collaborative project with Lincoln Laboratory, the IRRT has also been recently extended to be a decentralized planner for a network of mobile sensors.

As UAVs and MAVs are asked to carry out more complex tasks in more complex environments, further progress will be required in developing novel perception and state estimation algorithms, and incorporating richer models of uncertainty into the system. This research will lead to UAVs working in proximity to soldiers on the ground, monitoring the environment, and warning of threats. Similarly, this research will lead to UAVs working as part of first-responder teams, entering buildings ahead of their human partners, locating threats, and providing rich situational awareness. AeroAstro's strong capabilities in probabilistic inference and computationally efficient models of planning and learning are essential for addressing the future challenges. →

Flow visualizations, such as this for high angle-of-attack perching experiments, enable researchers to obtain information that may lead to greater agility for autonomous aircraft. (Jason Dorfman/CSAIL photo)



AUTONOMOUS MOBILITY

Novel Tools and Routing Algorithms’ Impacts Range from Daily Commutes to Space Travel

By Emilio Frazzoli, Jonathan P. How, Nick Roy, Russ Tedrake, and Brian Williams

A central Aeronautics and Astronautics Department research theme is development of methods that enable vehicles to move faster, farther, and with better maneuverability, while ensuring safety and minimizing environmental impact. AeroAstro faculty and students are pursuing these objectives, not only in the aerospace domain, but also in automotive applications and robotic systems.

AIRCRAFT CONTROL

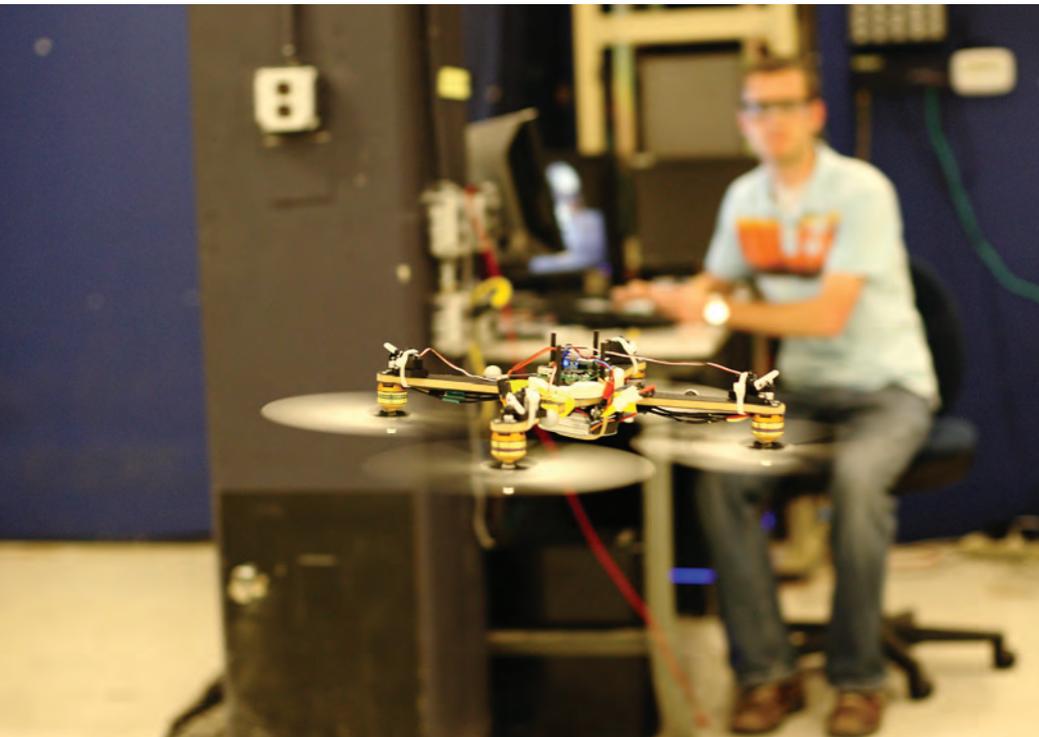
Developing ways to control agile, highly maneuverable aircraft is one of AeroAstro’s prime research areas. Using the unique capabilities of the RAVEN (Real-time indoor Autonomous Vehicle test ENvironment) indoor flight testbed, the Aerospace Computational Design Lab is tackling challenging mobility problems for autonomous aircraft. For example, real-time optimization techniques were used to enhance aerial combat decision making in an effort to advance the capabilities of UAVs in a one-on-one “dogfight” with other aircraft. Simulation results showed a significant 19% improvement over the current state-of-the-art for the problem formulation considered. RAVEN test flights demonstrated the real-time capability of these techniques with two radio-controlled aircraft.

We have also tested model reference adaptive control techniques using quadrotors—small four-rotor aircraft—and unconventional flight vehicles such as a three-wing vertical takeoff and landing aircraft, to enhance flight agility and robustness. Results showed noticeably improved performance during nominal flight and throughout failures. Indeed, in quadrotor tests, near-nominal stability was maintained after the sudden removal of a significant portion (half the chord) of one rotor. Continuing research on the agile control of fixed wing aircraft in a configuration where the aircraft “hangs” vertically from its propeller, state-of-the-art nonlinear and optimal control methods have both been used to generate and optimize trajectories from hover

to forward flight and back. Flight results showed close model matching and repeatability for maneuvers such as a transition from takeoff to prop hang hover over a horizontal distance of less than six meters.

Recently, we’ve developed and tested a novel variable-pitch quadrotor. The vehicle can perform maneuvers beyond the capabilities of the standard fixed-pitch quadrotor, such as inverted flight, rapid changes in vertical flight direction, and very rapid half-flips, with very little change in altitude.

A new project of the Computer Science and Artificial Intelligence Laboratory and the Laboratory for Information and Decision Systems, in collaboration with Harvard biolo-



The Aerospace Computational Design Lab’s novel variable-pitch quadrotor performs maneuvers beyond the capabilities of off-the-shelf fixed-pitch quadrotors, including flying upside down, as this one demonstrates. (Bernard “Buddy” Michini/MIT photo)

gists, seeks to understand how birds fly in cluttered environments, enabling us to design aircraft with similar abilities. This project builds on several years of work on understanding fixed- and flapping-wing flight at high angles of attack. Recent work was aimed at perching a small aircraft on a power line by sensing the line's magnetic field. Also, new analysis tools yield an understanding of fundamental limitations in high-speed flight in a cluttered environment: for example, a distinct speed threshold was discovered under which a small aircraft or a bird can fly indefinitely in a random forest with a certain tree density. Flight at speed higher than this threshold will unavoidably lead to a crash, within a distance that is exponentially decaying with the speed excess. Researchers are conducting experiments with birds in random environments to test applicability of these results.

PLANETARY EXPLORATION

NASA's Spirit and Opportunity rover missions revolutionized planetary exploration through their extensive traversal of the Martian surface. However, many locations of great scientific interest were inaccessible to the wheeled vehicles, such as a site of ancient springs that emerged from canyon walls. This type of terrain is better suited to the robotic equivalent of mountain goats. Under the direction of Professor Brian Williams, with the assistance of Professor Julie Shah, the Model-based Embedded and Robotic Systems (MERS) group, has developed methods for controlling walking machines, guided by qualitative "snapshots" of walking gait patterns. These control systems achieve robust walking over difficult terrain by embodying many aspects of a human's ability to restore balance after stumbling, such as adjusting ankle



Understanding how birds fly through cluttered environments, like a dense forest, could help better control autonomous aircraft. MIT researchers are working with Harvard biologists who have equipped birds like this one with motion-capture markers and flown them through simulated forests, with the objective to learn more about how they accomplish this. (Huai-Ti Lin/Harvard University photo)



The Model-based Embedded and Robotic Systems group has developed methods for controlling walking machines and applied them to such vehicles as such as the NASA Jet Propulsion Lab's Athlete robot, a six-legged/wheeled lunar rover that performs heavy lifting and manipulation tasks by using its legs as arms.
(Julie Shah/MIT photo)

support, moving free limbs, and adjusting foot placement. During the 2006–07 AeroAstro space capstone course, juniors and seniors, together with the MERS Group, Space Systems Lab, and JPL Caltech, developed Moretta, a wheeled, walking Mars rover, controlled via this robust concept for walking. During 2009 and 2010, MERS 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.

AUTOMOTIVE

In November 2007, six robotic vehicles made history as the first to complete the Defense Advanced Research Projects Agency's Urban Challenge, a competition for autonomous robotic vehicles, driving without human intervention or supervision for 55 miles in traffic, at speed, in an unstructured urban environment. Among them was MIT's entry: Talos, a heavily modified Land Rover LR3. AeroAstro faculty and students played a key role in Talos'

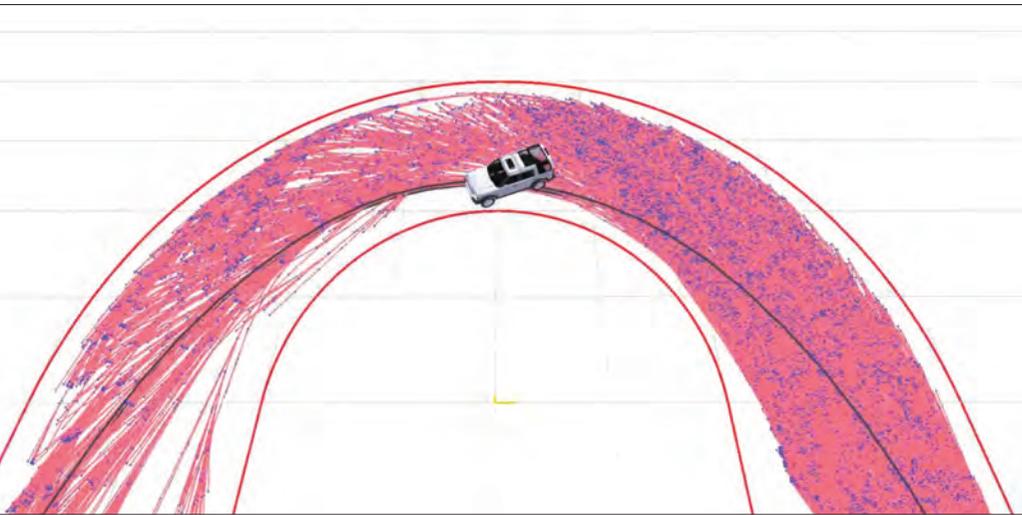
development, developing the autonomous vehicle's real-time planning and control system. The system, based on an algorithm called Rapidly-exploring Random Trees, could drive the three metric ton vehicle at speeds up to DARPA's 35 mph mandated limit in an urban-like environment, interacting safely with other vehicles, human-driven or robotic.

As a follow-up to this project, a similar team is working on a robotic forklift, aimed at automating logistics. The robotic forklift can autonomously pick up pallets from a truck bed and then place them in a designated spot at a storage facility.

A limitation of the planning and control algorithm used in the DARPA Urban Challenge that became apparent while operating the forklift in an unstructured environment was that the baseline RRT algorithm often failed to find efficient paths. LIDS researchers overcame this limitation, designing an algorithm called RRT*, which provably converges to globally asymptotic solutions, while maintaining a computational cost that is comparable to its baseline version.

The algorithm is broadly applicable to enable high-performance mobility in a variety of contexts. Not only does this substantially improve the quality and repeatability of a forklift's behavior; it also enables fast and reliable computation of optimal cornering trajectories over loose terrain, which would be important for off-road vehicles. It also enhances maneuvers used by human rally drivers, such as trail braking, a technique that allows fast cornering by carefully managing braking and counter steering. In addition, the algorithm outperformed all other available state-of-the-art algorithms in a robotic manipulation task involving a humanoid robot with 14 degrees of freedom. Specialized versions of the algorithm demonstrated speed improvements by a factor of 20 or more, exploiting the unique computational capabilities of Graphics Processing Units, which are now common in most standard laptops.

**A LIDS-DEVELOPED
ALGORITHM
OUTPERFORMS ALL STATE-
OF-THE-ART ALGORITHMS
IN A ROBOTIC
MANIPULATIONS TASK
INVOLVING A HUMANOID
ROBOT WITH 14 DEGREES
OF FREEDOM.**



A computer-generated optimal trajectory for cornering on loose surfaces, recovering maneuvers performed by expert human drivers. (Jeonghwan Jeon/MIT image)

Finally, techniques first developed in the early 2000s leading to the first autonomous aerobatic helicopters that could perform challenging maneuvers such as split-Ss, barrel rolls, and hammer-head turns, were used to design control laws for high-performance off-road driving. It was shown that maneuvers such as trail braking can be decomposed into sequences of “motion primitives,” including equilibrium trajectories at very large sideslip angles, which can be stabilized using only longitudinal inputs (gas and brake pedals).

Interestingly, techniques based on teaching humans a small number of elementary motions were also effective in designing training programs for humans to operate in (simulated) microgravity.

TRANSPORTATION NETWORKS

As we all know from being stuck in rush hour traffic, one vehicle’s mobility often depends more on the density of other vehicles nearby or on environmental effects, than on its own capabilities. For example, in August 2010 a 100 km Chinese traffic jam took almost 10 days to clear. The 2010 Eyjafjallajökull volcano eruption caused a six-day air traffic disruption across Europe.

In fact, mobility in an urban environment or in a congested airspace is better studied as a collective phenomenon, influenced by environmental conditions, rather than as an individual vehicles, performance. LIDS researchers have studied the effect of environmental degrada-

tion, ranging from bad weather to navigational aid failures, on air traffic throughput. Also, new methods were designed to identify clusters of trajectories detect outliers (i.e., aircraft that are not conforming to “normal” behaviors), and to optimize the aircraft flow.

In terms of ground transportation, researchers are developing new tools to analyze road traffic and its response to disruptions, such as accidents or road closures. By a novel formulation of transportation networks as a dynamical system driven by informed drivers, they characterized not only the stability of equilibria (i.e., whether individual drivers will collectively converge to these equilibria), but also their robustness. Researchers showed that under some conditions, equilibria are very sensitive to small disruptions, which can cause traffic gridlock through a cascading effect. In addition, they were able to determine the characteristics of robust equilibria able to avoid such catastrophic failures. Work is under way to determine mechanisms by which robust equilibria can be attained, so that disruptions will have a minimal effect on the overall citywide traffic flows.

The novel analysis tools and routing algorithms our faculty and students are developing will eventually enable reliable, fast, and environmentally friendly transportation options for people and goods that could range from the daily commute, to air transportation, and even to interplanetary travel. ➔



The Space Systems Engineering multi-semester capstone sequence designs, builds, and operates craft for operation in space. These include research spacecraft on the International Space Station, innovative weather-monitoring satellites, and devices like ExoplanetSat, pictured here with the capstone class students, which is a three-unit cubesat equipped with an optical system to observe a star for one year, detecting any orbiting Earth-like planets. Autonomy and automatic control are central themes in each project since these spacecraft must autonomously point, maneuver, recharge, and monitor their health. (William Litant/MIT photo)

ACADEMICS AND AUTONOMY

MIT Autonomous Systems Education: Training the Next Generation

By Brian C. Williams

The technological world is in the early stages of a revolution in autonomous and unpiloted systems that is influencing every aspect of aerospace and beyond, including in space, in the air, on the surface, and deep within the ocean.

These offerings are particularly distinct at the undergraduate level. Our curriculum enables students to explore many of the fascinating sub-areas of autonomous systems design and operation.

The Department of Aeronautics and Astronautics, MIT's Course 16, has developed a breadth of educational options for students to explore autonomy that is unique for aerospace, mechanical, and computer science departments. These offer-

THE NEED FOR AUTONOMOUS OPERATIONS

The aerospace field is the birthplace of the autonomous system revolution, which started in space and expanded into the air. In the 1990s, research in autonomous systems was driven by the increased complexity of space missions, which quickly transitioned from flyby missions, such as Voyager, to orbiters, such as Galileo and Cassini, and on to in-situ missions, such as Mars Pathfinder and Sojourner, and the Spirit and Opportunity rovers. The increase in mission complexity led to increased mission failures, such as the loss of the flagship Mars Observer mission in the early '90s. This was the first return to Mars after Viking, and the loss of Mars Polar Lander and Climate Orbiter at the end of that decade, which were two of the last "faster, cheaper, better" missions developed by NASA. NASA's transition to orbiters and landers introduced the need for space systems that can repair themselves and complete

their mission without human intervention, rather than calling to Earth for help. Finally, the transition to in-situ missions, such as Mars rovers, introduced the need for space systems to be operated on a daily cycle, rather than being pre-scripted months to years in advance.

These missions gave birth to the subfield of autonomous operations, which focuses on systems that use engineering models to automatically generate operational control sequences from high-level mission goals, to diagnose and repair themselves, and to efficiently manage their limited resources. The field of autonomous operation tightly couples to the fields of safety critical systems, humans and automation, and software engineering. The emerging area of autonomous science operation expands the capabilities of autonomous operation to the development of science explorers that autonomously gather information in order to best improve scientific models or to classify new phenomena. Significant demonstrations of autonomous operation include the Remote Agent experiment on NASA's Deep Space One Probe, an asteroid-comet fly-by mission, and the Autonomous Science-craft experiment on Earth Observer One, an Earth orbiting environmental monitoring mission.

NEW FIELDS FOR THE NEXT GENERATION

Industry is faced with the challenge that a traditional aerospace degree does not equip engineers with all the skills necessary to conceive, design, implement, operate, and research new technologies for these highly autonomous, and often safety critical systems. As Apollo-era engineers are now retiring or retired, industry is looking to hire new engineers with exactly these skills. MIT AeroAstro's 16-2 Aerospace Engineering with Information Technology degree and 16-ENG Flexible Engineering degree are designed to train the next generation of aerospace engineers to effectively exploit these new technologies.

In recent years, the success of autonomous systems has expanded from space to unmanned air and ground vehicles. The military makes extensive use of these capabilities and they are beginning to expand into the science arena, through environmental monitoring missions operated in the air and the sea, and into the transportation arena, through autonomous personal ground and air vehicles.

Autonomous vehicles have been a major driver for two additional subfields. One is mobile robotics, which focuses on autonomously determining the location of a vehicle, navigating the vehicle, and on mapping the area that the vehicle traverses. It has also been a major driver for the field of human systems engineering, which focuses on the effective interplay between humans and automation in



general, with autonomous vehicles and robots being two important instances. Significant demonstrations of autonomous vehicles include the DARPA Urban Vehicle Challenge, international competitions on autonomous quadrotors, and Boeing's concept of the personal transportation system—an air vehicle reminiscent of the Jetson's car.

A third exciting area, just emerging, is robotic networks. NASA envisions a global sensor web, in which all of its Earth orbiting satellites are coordinated as a single observatory that can autonomously respond to episodic events, such as a forest fire, a volcano eruption, or a toxic algal bloom. MIT's Lincoln Lab is pursuing a similar concept that coordinates satellites, air vehicles, and ground radar in support of homeland security, while the National Science Foundation is developing infrastructure for controlling ocean observing systems composed of buoys, underwater gliders, and powered vehicles. The development of robotic networks requires expertise in the subareas of autonomous operation, mobile robotics, and human systems engineering, mentioned above. The additional subareas of communication and distributed systems become essential.

SPHERES microsatellite research on the International Space Station is central to a new Science, Technology, Engineering, and Mathematics Education Coalition education program coordinated by AeroAstro called Zero Robotics. In this program, middle and high school students nationwide (soon to be worldwide) test their skills in a competition, programming SPHERES to conduct autonomous operations in space. The competition finals are conducted live via downlink from the Space Station to MIT while the students observe. (William Litant/MIT photo)

CURRICULA RICH IN AUTONOMOUS SYSTEM LEARNING PATHS

AeroAstro's undergraduate and graduate curricula offer students a rich set of paths, at a range of depths, for developing the professional expertise needed to create each of these types of autonomous systems. Undergraduate students can focus on methods for making systems more autonomous through the 16-2 Aerospace Engineering with Information Technology degree, or they can focus on the hardware design of a next generation unmanned air or space vehicle through the 16-1 Aerospace Engineering degree. Alternatively, students can use the 16-ENG Flexible Engineering degree to delve deeper, by concentrating on an autonomous system subfield, such as mobile communication, or to couple autonomous systems with a societal need, such as environmental monitoring. Through the department's capstone design sequence, students learn to work as a team to create an unmanned air or space vehicle system. Students also have the opportunity to work with world-class researchers to pursue cutting edge research on autonomous systems, through MIT's Undergraduate Research Opportunities Program and AeroAstro's experimental design sequence.

The 16-2 Aerospace Engineering with Information Technologies degree offers an ideal opportunity to develop a broad background in aerospace vehicle design and information technologies needed to create a range of autonomous systems. The degree begins with a core of courses in aerospace vehicle design, including materials and structures, thermodynamics and propulsion, fluid dynamics, coupled to a core of courses in information engineering, including dynamics, feedback control, signals and systems, computer programming, and probability and statistics. A hallmark of the department is our unified approach to teaching four of these subjects and their interdisciplinary interactions.

Layered on top of the core are professional area subjects and electives that offer broad exposure to the disciplines needed to develop robust, highly autonomous, mission-critical systems, including principles of autonomy and decision making, human factors engineering, real-time systems and software, digital systems laboratory, robotics: sciences and systems, feedback control systems, and communication systems and networks.

Principles of Autonomy and Decision-making teaches the algorithmic foundations necessary for creating autonomous systems and for intelligent decisions aids. This includes algorithms for goal-directed planning and execution, which are common to all types of autonomous systems, algorithms for resource allocation, diagnosis, and repair, which are common to autonomous operations, and algorithms for localization, path planning, and model-predictive control, which are common to mobile robotics. Topics are organized around four foundational areas: state-space search, constraint satisfaction, optimization, and reasoning under uncertainty.

Effective coordination between humans and automation is absolutely critical to creating robust autonomous systems. *Human Factors Engineering* teaches a fundamental understanding of the human factors that must be considered in the design and engineering of complex aerospace systems, with a focus on the derivation of human engineering design criteria from sensory, motor and cognitive sources.

Navigation, manipulation and control are essential to creating robust autonomous vehicles and mobile robots. *Feedback Control Systems* teaches the state-space approach to control system analysis and design, including state estimation and design of dynamic control laws, while covering performance limitations and robustness. *Robotics: Sciences and Systems* teaches the software elements of the design of mobile robots, with topics including kinematics and dynamics; motion planning and manipulation; and state estimation, tracking, and map building.

Finally, robust communication is essential to the emerging area of robotic networks. *Communication Systems and Networks* introduces the fundamentals of digital communication and networks, with application to aircraft, satellite and deep space communication. Communication topics covered include information theory, sampling, quantization and coding, and system performance in the presence of noise, while data networking topics include reliable packet transmission, routing, and internet protocols.

**EFFECTIVE COORDINATION
BETWEEN HUMANS AND
AUTOMATION IS ABSOLUTELY
CRITICAL TO CREATING ROBUST
AUTONOMOUS SYSTEMS.**

Stepping back, through the 16-2 Information Engineering degree, students achieve breadth in the disciplines underpinning autonomous systems by choosing at least three of the above courses, while receiving depth in traditional aerospace engineering through the department's extensive core.

Alternatively, students may use the 16-ENG Flexible Engineering degree to serve several goals:

- » shift their emphasis from the core aerospace courses to those more directly related to engineering autonomous systems
- » develop greater expertise in one sub-discipline relevant to autonomous systems,
- » develop background in the application discipline in which autonomous systems are deployed.

16-Eng reduces the aerospace core, while retaining the department's hallmark unified and capstone design experiences. It offers students tremendous flexibility through a concentration of six coherent subjects, which a student designs in consultation with a faculty advisor. The department has introduced a series of pre-defined concentrations, many of which are relevant to a student interested in autonomous systems. First and foremost, the Autonomous Systems concentration starts with a foundation in the mathematics and algorithms underlying autonomous decision-making and control. It builds upon this a focus in one of three technology areas: embedded systems, robotics, and humans, systems and automation, which closely relate to the topic areas discussed earlier in this article.

Students may also specialize in one of the related sub-disciplines discussed earlier; for example, through concentrations in Software Engineering or Communication and Networking, or through a novel concentration that the student designs.

Alternatively, many students are interested in autonomous systems because of their potential for meeting a societal need. Students can design or choose a concentration that balances subjects in a problem domain and in autonomous systems. To this end, the 16-ENG program has pre-defined concentrations in Space Exploration, Transportation, Energy, and the Environment, which students can use as a source of inspiration and guidance.

Aerospace engineering is one of the most skilled disciplines in designing innovative, complex systems that robustly perform time and safety critical missions. A hallmark of the MIT AeroAstro undergraduate experience is a two to three semester capstone experience, directed towards conceiving, designing, implementing, and operating an innovative aerospace system. Each year, all students in a class work as a team to design either a

space or aeronautic system. Most of these space and aeronautic systems are unmanned, and have become increasingly autonomous over the years.

For example, during 2006 and 2007 students developed a Mars Rover, called Moretta (<http://www.csail.mit.edu/videoarchive/research/robo/legged-locomotion>), that could move quickly across smooth terrain using wheels, and could “pick up its feet,” using four legs to traverse more difficult terrain. Sixty-six students divided into three teams, to develop and implement concepts for the legged rover, autonomous walking, and human-robot interaction, and were mentored and reviewed by autonomy researchers from the MIT Model-based Embedded Robotic Systems group, spacecraft engineers from the MIT Space Systems Lab, and Mars roboticists from NASA’s Jet Propulsion laboratory. Subsequently, MIT graduate students employed these concepts to control JPL’s Athlete lunar rover, a walking rover that can use its legs as arms to perform manipulation. →



AeroAstro capstone course students assemble Moretta, a legged planetary rover they designed and built to traverse terrain that would stymie a wheeled vehicle. (William Litant/MIT photo)



ALUMNI INTERVIEW

YOU DON'T NEED A PILOT WHEN YOU HAVE DAVE VOS

From a robot unicycle to commercial aircraft flight controls systems, this AeroAstro alum has focused his career on cutting edge robotic controls.

By Richard Dahl

Dave Vos, AeroAstro Ph.D '92, with a Athena GuS flight control and navigation systems, Rockwell Collins Control Technologies' smallest integrated INS, GPS, air data sensor suite, and flight control system. Vos founded Athena Technologies in 1998; 10 years later, Athena was purchased by Rockwell Collins where Vos is now senior director. (Rockwell Collins photo)

David Vos is senior director at Rockwell Collins Control Technologies. Vos, who received his Ph.D. from MIT AeroAstro in 1992, has devoted his career to the development of high-performance flight-control systems and autopilots. While at MIT, he built what is believed to be the world's first robotic unicycle and then applied the relevant theories to flight control. In 1998 he founded Athena Technologies, which developed and manufactured flight-control systems for unmanned air vehicles. Athena produced the GuideStar family of flight control systems for applications on commercial aircraft, UAVs, target drones and missiles. In 2008, Athena was purchased by Rockwell Collins, which is continuing the Athena product line. Vos is a native of South Africa, where he received an undergraduate degree in engineering at the University of Stellenbosch. He lives in Dela Plane, Va.

Q. How did you get interested in this line of work?

Vos: This whole topic actually goes way back to when I was an undergraduate in South Africa in the early '80s and recognizing that there was quite a significant need for very structured ways to design and develop autopilots or control systems. I remember telling my brother I wanted

to go to MIT and learn everything there is to know about control systems and find a way to design and develop them that is much more synthesis and much less ad hoc than the current state of the art was in the late '70s and early '80s.

Q. Tell me about your unicycle robot work at MIT and how it applied to flight control.

Vos: It was a robot that had a turntable on top packed with batteries, which simulated the torso motion of a human rider; and it had two DC electric motors, one for controlling the pitching motion and one for controlling the torso motion of a human rider. Because it had all the equivalent attributes of flying, it was a very nice way to demonstrate the control theory, adaptive and non-linear, and to develop it so that it fits to where I wanted it to go, which is to have these capabilities for synthesizing solutions, rather than the ad hoc element that prevailed back then.

It turned out that the non-linear, adaptive approach worked very well and I could demonstrate the solution on the robot as part of my Ph.D. work. It all worked nicely. But it was not really ready for the airplane control-design problem. So I had to do more work after MIT to get that level of the problem—and the answer—defined. By 1998 it was all ready to go. I'd done consulting work from my basement on all kinds of applications, and one of them was (MIT alumnus) John Langford's company (Aurora Flight Sciences)—I did several control systems on several of his earlier UAVs and that's how my relationship with John started.

John and I co-founded Athena in 1998 and then, by the early 2000s, basically I was running Athena and we showed

significant growth. I wanted to take this to a much higher level. I see the future of integrated manned and unmanned air space as an example of what's really possible with the degrees of automation and autonomy that we do today in a very run-of-the mill fashion. I want to get that into all of aerospace—military, civilian, commercial. There's a real set of opportunities to come in aerospace.

Q. What were the early days like at Athena?

Vos: In the very early days, we actually rented one office at John's company. We started from nothing. I had a steady rate at which I was generating patents and we raised a small amount of venture-capital money, but the timing was right. The UAV market was beginning to show promise. MEMS sensor technology (micro-electrical mechanical systems sensor) was just becoming something real in the late '90s and early 2000s and microprocessors were becoming quite powerful. Those three things together made it really possible to package these highly integrated sensors, computers, and the non-linear control algorithms together.

Q. So, basically, this technology is a box, correct?

Vos: Yes. The other important thing that we did was we took functions that would be in five or six different boxes and rolled it into one box. That's why it was so critically enabling to have microprocessors and the MEMS sensor technology come along because suddenly we could package. Gosh, one of our boxes weighs only four ounces, and that is a complete, integrated sensing suite, GPS, flight computer, mission computer. Everything is in that single box to be a complete flight-control and sensing system.

Q. What was it like for you to move from a small company setting to a big one?

Vos: It's been an interesting growth trajectory. In the early '90s I was working from my basement in a one-man show, contracting to things as diverse as expert-witness work to helping John make his UAVs. And then growing the company, through setting up infrastructure and developing a quality system that is not just a police system but in fact one that everyone embraces. Honestly, when we became part of Rockwell Collins, you might be surprised but we were just as strict as a small company in business and engineering/development processes as 20,000-employee Rockwell Collins. So it wasn't a big leap.

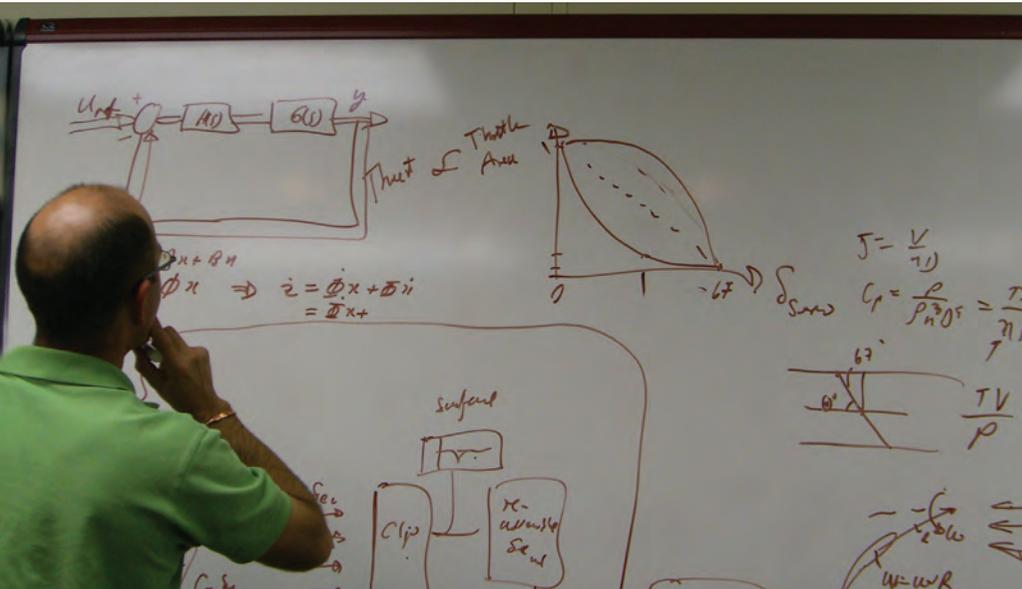
Q. Who are your clients?

Vos: Our clients today are mostly military because UAVs are mostly military. And it's all over the world. You name a UAV company and we are pretty much on (their aircraft), either with a flight-control system or, now that we're part of Rockwell, we have several communications-networking solutions. So we have content on almost every single UAV program in the world today. Our intent is to continue to grow that presence.

Q. Do you envision a growing non-military use for UAVs?

Vos: If you don't call it a UAV, but you call it an automatic or autonomous capability within an airplane, then,

whether there's a pilot driving or not sort of becomes a secondary question. It becomes more of an economics question. For example, do you want to have one pilot in a four-seat airplane or two pilots if you want to carry passengers? But if you have two pilots, it makes it very difficult because you're taking another seat out of the four seats. But if you have one pilot, it makes some business models possible, such as air taxis. If you have highly reliable, redundant solutions on manned and unmanned airplanes, the cultural gap and the technological gap between the airplane with the human in it and the airplane without it becomes very small.



Vos has created the David and Patricia Vos Foundation, which annually sponsors a full-time scholarship for an MIT AeroAstro Ph.D. student. It enables him "to scratch someone else's back to help enable opportunity."

Then the dialogue becomes more “How do we manage the things that are in the air space, how do we ensure that they have the right level of equipment on board, whether they’re manned or unmanned.” With that view, I’m very enthusiastic about the future of aerospace—or actually, the air space. You would have lots of capabilities. You could fly medivac missions into dangerous areas with helicopters and push a “go home” button and the airplane goes back on its own to take casualties out, or brings in new supplies. There are a broad range of applications: fire observations, cargo transport ... and there will be new businesses that spring up, once it is barrier free to get high degrees of automation and autonomy into the air space.

Q. It almost sounds like human pilots might go the way of the dodo.

Vos: (Laughing) I kind of think not. The economics will be the driver. I would put it this way: The traditional human pilot of 50 years ago who has to have his hands and feet on the stick and rudders and worrying about throttles and mixtures ...that’s all going to fade away because we have such high degrees of autonomy and automation on board. It’s more vehicle manager than having to fly seat of your pants. That’s going to be the big enabler because then, whether that person is in the cockpit itself or elsewhere is really the difference between is the data going over a data link to a remote operator or if it’s going to some panels inside a cockpit. It’s really not very different. So I don’t think pilots are going to go away; they’re just going to change flavor. I think pilots should be really enthusiastic because if you proliferate activity in the air space, then

there are going to be many more opportunities. There’s going to be a higher level of operational management of these systems, so there’s a significant need there.

Q. Do you have an ongoing relationship with MIT?

Vos: I do. I set up a foundation, which sponsors a full-time scholarship for a Ph.D. student every year in the AeroAstro Department. It’s called the David and Patricia Vos Foundation, for my wife and me. I had a Sloan scholarship and several other scholarships when I was at MIT. It’s time for me to scratch someone else’s back to help enable opportunity. It’s fun to make a small contribution.

Q. Looking to the future, what impact do you hope automated flight-control systems might have?

Vos: My dream today is: I don’t want to own a business jet until I can have all this infrastructure in place to the point where, if I want to fly it today, hands on, I can do that; but if I’m too busy I want to drive from here to the local airport where it’s parked, and on the way just drop into Google or somewhere, what my destination is, and by the time I get there I’d be able to just push a button with a flight plan already approved, the plane will take me there automatically and I can do other things. I really believe in that future, it’s not that far away, there are some cultural challenges, but my mission is to make that happen.

Q. Sounds like The Jetsons.

Vos: (laughing) I think The Jetsons are just around the corner. →



LAB REPORT: A 2010-11 Review of Aeronautics and Astronautics Department Laboratories

Information provided by the research laboratories and research centers.

Aboard the International Space Station and wearing MIT 150 anniversary t-shirts, MIT alumni-astronauts (left) Mike Fincke '89, Cady Coleman '83, and Greg Chamitoff Ph.D. '92, show three of the Space Systems Lab's SPHERES micro-satellites. The image is from a downlinked video the astronauts made for high school students participating in the Zero Robotics Competition coordinated by the lab. (NASA video image)

AEROSPACE COMPUTATIONAL DESIGN LABORATORY	49
AEROSPACE CONTROLS LABORATORY	49
AEROSPACE ROBOTICS AND EMBEDDED SYSTEMS GROUP	50
THE AUTONOMOUS SYSTEMS LABORATORY	51
COMMUNICATIONS AND NETWORKING RESEARCH GROUP	52
COMPLEX SYSTEMS RESEARCH LABORATORY	53
GAS TURBINE LABORATORY	53
HUMANS AND AUTOMATION LABORATORY	54
INTERNATIONAL CENTER FOR AIR TRANSPORTATION	55
LABORATORY FOR INFORMATION AND DECISION SYSTEMS	56
LEAN ADVANCEMENT INITIATIVE	56
THE LEARNING LABORATORY	57
MAN VEHICLE LABORATORY	58
THE PARTNERSHIP FOR AIR TRANSPORTATION NOISE AND EMISSIONS REDUCTION	59
SPACE PROPULSION LABORATORY	60
SPACE SYSTEMS LABORATORY	60
TECHNOLOGY LABORATORY FOR ADVANCED MATERIALS AND STRUCTURES	62
WIRELESS COMMUNICATION AND NETWORK SCIENCES GROUP	63
WRIGHT BROTHERS WIND TUNNEL	65

AEROSPACE COMPUTATIONAL DESIGN LABORATORY

The Aerospace Computational Design Laboratory's mission is the advancement and application of computational engineering for aerospace system design and optimization. ACDL researches topics in advanced computational fluid dynamics and reacting flow, methods for uncertainty quantification and control, and simulation-based design techniques.

The use of advanced computational fluid dynamics for complex 3D configurations allows for significant reductions in time from geometry-to-solution. Specific research interests include aerodynamics, aeroacoustics, flow and process 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.

Uncertainty quantification and control is aimed at improving the efficiency and reliability of simulation-based analysis as well as supporting decision under uncertainty. Research is focused on error estimation, adaptive methods, ODEs/PDEs with random inputs, certification of computer simulations, and robust statistical frameworks for estimating and improving physical models from observational data.

The creation of computational decision-aiding tools in support of the design process is the objective of a number of methodologies the lab pursues. These include PDE-constrained optimization, real time simulation and optimization of systems governed by PDEs, multiscale 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 and staff include: Dave Darmofal (director), Doug Allaire, Mark Drela, Robert Haimes, Youssef Marzouk, Cuong Nguyen, Jaime Peraire, QiQi Wang, and Karen Willcox.

Visit the Aerospace Computational Design Laboratory at <http://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 areas such 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. Recent research includes the following:

Robust Planning: ACL developed a distributed task-planning algorithm that provides provably good, conflict-free, approximate solutions for heterogeneous multi-agent/multi-task allocation problems on random network structures. The consensus-based bundle algorithm has since been extended to include task time-windows, coupled agent constraints, asynchronous communications, and limited network connectivity. CBBA has been used to plan for both networked UAV/UGV teams and human-robot teams, and real-time performance has been validated through flight test experiments. Recent path planning research has yielded chance constrained rapidly-exploring random trees, a robust plan-

ning algorithm to efficiently identify trajectories, which satisfy all problem constraints with some minimum probability. Finally, in collaboration with Professor Nick Roy's group, ACL developed an efficient approach for modeling dynamic obstacles with uncertain future trajectories, through the use of Gaussian processes coupled with an RRT-based reachability evaluation.

UAV Mission Technologies: ACL has 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. As part of research on long-duration UAV mission planning, ACL has also constructed an autonomous recharge platform, capable of autonomous battery replacement for small UAVs.

Information-Gathering Networks: Recent ACL research has addressed maximizing information gathering in complex dynamic environments, through 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 developed methodologies that correctly and efficiently quantify the value of information in large information spaces, such as a weather system, leading to a systematic architecture for mobile sensor network design. 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.

Multi-Agent Decision-Making: Markov Decision Processes are a natural framework for formulating many decision problems of interest; ACL has identified approximate solution techniques which can utilize this framework while

overcoming the curse of dimensionality typically encountered for exact solutions. By exploiting flexible, kernel-based cost approximation architectures, ACL's Bellman Residual Minimization algorithm computes an approximate policy by minimizing the error incurred in solving Bellman's equation over sampled states. For online systems, ACL introduced incremental Feature Dependency Discovery algorithm that expands the representation in areas where the sampled Bellman error persist. iFDD is convergent and computationally cheap, hence amenable to systems with restricted thinking time between actions. Finally, ACL has developed fast, real-time algorithms for solving constrained MDPs in uncertain and risky environments while maintaining probabilistic safety guarantees.

ACL faculty are Jonathan P. How and Steven Hall.

Visit the Aerospace Controls Laboratory at <http://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, queueing theory and stochastic systems, with randomized and distributed algorithms, formal languages, machine learning, and game theory.

Current research areas include:

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: namely, 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.

ARES is directed by Emilio Frazzoli.

Visit the Aerospace Robotics and Embedded Systems group at <http://groups.csail.mit.edu/mers/>



In the Aerospace Robotics and Embedded Systems laboratory, (from left) Prof. Emilio Frazzoli, post-doc Maxime Gariel, and Ph.D. student Josh Bialkowski examine a powered autonomous skateboard they are developing as an exercise in mobility-on-demand systems. Designed for use by multiple people, the board would be easier to ride than a conventional skateboard, and capable of traveling on its own to a recharging station and then to the next user. (William Litant/MIT photo)

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 Robotics (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 in length, 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 <http://www.csail.mit.edu/videoarchive/research/robo/auv-planning>)

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

MERS, in collaboration with Boeing, has demonstrated in simulation the concept of an autonomous personal air vehicle, called PT, in which passengers interact with the vehicle in the same manner that they interact today with a taxi driver. (Video at <http://www.csail.mit.edu/videoarchive/research/robo/personal-aerial-transportation>.)

- » A third demonstration involves 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. During 2009 and 2010, 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. (Video at <http://www.csail.mit.edu/videoarchive/research/robo/athlete-mers>.)

ASL faculty are Brian Williams and Nicholas Roy.

Visit the Model-based Embedded Systems group at <http://groups.csail.mit.edu/mers/> and the Robust Robotics Group at <http://groups.csail.mit.edu/rrg/>

COMMUNICATIONS AND NETWORKING RESEARCH GROUP

The Communications and Networking Research Group’s primary goal is the 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.

The group is working on a wide range of projects in the area of data communication and networks with application to sat-

ellite, wireless, and optical networks. Over the past year, the group continued to work on a Department of Defense-funded project toward the design of highly robust telecommunication networks that can survive a massive disruption that may result from natural disasters or intentional attack. The project examines the impact of large scale, geographically correlated failures, on network survivability and design. In a related project, funded by the National Science Foundation, the group is studying survivability in layered networks; with the goal of preventing failures from propagating across layers.

The group is also working on an Army MURI (Multi-disciplinary University Research Initiative) project titled “MAASCOM : Modeling, Analysis, and Algorithms for Stochastic Control of Multi-Scale Networks.” The project deals with control of communication networks and develops novel network control algorithms using techniques from stochastic control of dynamical systems. The project is a collaboration among MIT, Ohio State University, University of Maryland, University of Illinois, Purdue University, and Cornell University. In a related project funded by the National Science Foundation the group is exploring distributed network control algorithms that can be implemented with low computation and communication complexities.

CNRG’s research crosses disciplinary boundaries by combining techniques from network optimization, queueing theory, graph theory, network protocols and algorithms, hardware design, and physical layer communications.

Eytan Modiano directs the Communications and Networking Research Group.

Visit the Communications and Networking Research Group at <http://web.mit.edu/aeroastro/labs/cnrg>

COMPLEX SYSTEMS RESEARCH LABORATORY

Increasing complexity and coupling as well as the introduction of new digital technology are introducing new challenges for engineering, operations, and sustainment. The Complex Systems Research Lab designs system modeling, analysis, and visualization theory and tools to assist in the design and operation of safer systems with greater capability. To accomplish these goals, the lab applies a system’s approach to engineering that includes building technical foundations and knowledge and integrating these with the organizational, political, and cultural aspects of system construction and operation.

While CSRL’s main emphasis is aerospace systems and applications, its research results are applicable to complex systems in such domains as transportation, energy, and health. Current research projects include accident modeling and design for safety, model-based system and software engineering, reusable, component-based system architectures, interactive visualization, human-centered system design, system diagnosis and fault tolerance, system sustainment, and organizational factors in engineering and project management.

Nancy Leveson directs the Complex Systems Research Laboratory.

Visit the Complex Systems Research Laboratory at <http://sunnyday.mit.edu/csrl.html>

GAS TURBINE LABORATORY

The MIT Gas Turbine Laboratory has had a worldwide reputation for research and teaching at the forefront of gas turbine technology for more than 60 years. GTL’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.

Examples of current and past research projects include: engine diagnostics and smart engines, aerodynamically induced compressor rotor whirl, a criterion for axial compressor hub-corner separation, axial and centrifugal compressor stability prediction, losses in centrifugal pumps, loss generation mechanisms in axial turbomachinery, the Silent Aircraft Initiative (a collaborative project with Cambridge University, Boeing, Rolls Royce, and other industrial partners), hybrid-wing-body airframe design and propulsion system integration for reduced environmental impact (NASA N+2), counter-rotating propfan aerodynamics and acoustics, an engine air-brake for quiet aircraft, inlet distortion noise prediction for embedded propulsion systems, novel aircraft concepts for 2035 (NASA N+3), high-speed micro gas bearings for MEMS turbomachinery, small gas turbines and energy concepts for portable power, and carbon-nanotube bearings.

Faculty and research staff include: Elena de la Rosa Blanco, Fredric Ehrich, Alan Epstein (emeritus), Edward Greitzer, Claudio Lettieri, Jürg Schiffmann, Zoltan Spakovszky (director), Alejandra Uranga, and Choon Tan.

Visit the Gas Turbine Lab at
<http://web.mit.edu/aeroastro/labs/GTL/index.html>

HUMANS AND AUTOMATION LABORATORY

Research in the Humans and Automation Laboratory focuses on the multifaceted interactions of human and computer decision-making in complex socio-technical systems. With the explosion of automated technology, the need for humans as supervisors of complex automatic control systems has replaced the need for humans in direct manual control. A consequence of complex, highly-automated domains in which the human decision-maker is more on-the-loop than in-the-loop is that the level of required cognition has moved from that of well-rehearsed skill execution and rule following to higher, more abstract levels of knowledge synthesis, judgment, and reasoning. Employing human-centered design principles to human supervisory control problems, and identifying ways in which humans and computers can leverage the strengths of the other to achieve superior decisions together is HAL's central focus.

Current research projects include investigation of human understanding of complex optimization algorithms and visualization of cost functions, human performance modeling with hidden Markov models, collaborative human-computer decision making in time-pressured scenarios (for both individuals and teams), human supervisory control of multiple unmanned vehicles, and designing displays that reduce training time. Lab equipment includes an experimental testbed for future command and control decision support systems intended to aid in the development of human-computer interface design recommendations for future unmanned vehicle systems. In addition, the lab hosts a state-of-the-art multi-workstation collaborative teaming operations center, as well as a mobile command and control experimental test bed mounted in a Dodge Sprinter van awarded through the Office of Naval Research. Current research sponsors include the Office of Naval Research, the U.S. Army, Lincoln Labo-



Gas Turbine Lab director Professor Zoltan Spakovszky (wearing tie) answers questions about jet engines during the April 30, 2011 MIT Open House. On display in the AeroAstro Neumann Hangar were (clockwise, from left) a 1940s Junkers Jumo 004, a CFM56-3 of the 1980s/90s, and a GE 1-A Whittle design, also of the 1940s.

ratory, Boeing, the Air Force Research Laboratory, the Air Force Office of Scientific Research, Alstom, and the Nuclear Regulatory Commission.

HAL faculty include Mary L. Cummings (director), Nicholas Roy, and Thomas Sheridan.

Visit the Humans and Automation Laboratory at <http://mit.edu/aeroastro/labs/halab/index.html>

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 <http://web.mit.edu/aeroastro/labs/ICAT/>

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

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

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

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

LIDS is based in MIT's Stata Center, a dynamic space that promotes a high level of interaction within the lab and with the larger MIT community. Currently 17 faculty are affiliated with the laboratory, including Emilio Frazzoli, Jonathan P. How, Eytan Modiano, and Moe Win.

Visit LIDS at <http://lids.mit.edu/>

LEAN ADVANCEMENT INITIATIVE

The Lean Advancement Initiative is a learning and research consortium focused on enterprise transformation; its members include key stakeholders from industry, government, and academia. LAI is headquartered in AeroAstro, works in collaboration with the Sloan School of Management, and is managed under the auspices of the Center for Technology, Policy and Industrial Development, an MIT-wide interdisciplinary research center.

LAI began in 1993 as the Lean Aircraft Initiative when leaders from the U.S. Air Force, MIT, labor unions, and defense aerospace businesses created a partnership to transform the U.S. aerospace industry using an operational philosophy known as "lean." LAI is now in its sixth phase and focuses on a holistic approach to transforming entire enterprises across a variety of industries. Through collaborative stakeholder engagement, along with the development and promulgation of knowledge, practices, and tools, LAI enables enterprises to effectively, efficiently, and reliably create value in complex and rapidly changing environments. Consortium members work collaboratively through the neutral LAI forum toward enterprise excellence, and the results are radical improvements, lifecycle cost savings, and increased stakeholder value. LAI's international Educational Network provides LAI members with unmatched educational outreach and training capabilities and includes more than 60 educational institutions around the world.

AeroAstro LAI participants include Deborah Nightingale (co-director), Earll Murman, and Annalisa Weigel.

Visit the Lean Advancement Initiative at <http://lean.mit.edu>

THE LEARNING LABORATORY

The AeroAstro Learning Laboratory, located in Building 33, is a world-class facility developed to promote 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, video conferences 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.
- » The Project Office—team-focused work and meeting spaces, which may be assigned to teams for weeks or months, or kept available as needed. This room support individual study, group design work, online work, and telecommunication.
- » 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, and is outfitted with a number of flight simulator computer stations.

Digital Design Studio. The Digital Design Studio, located on the second floor, is a large room with multiple computer stations arranged around reconfigurable conference tables. Here, students conduct engineering evaluations and design work, and exchange computerized databases as system and subsystem trades are conducted during the development cycle. The room is equipped with information technologies that facilitate teaching and learning in a team-based environment. Adjacent and networked to the main 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 Center, positioning him for convenient assistance.



In the Man Vehicle Lab, visiting high school students learn from Professor Dava Newman about the BioSuit design concept for future spacesuits. (William Litant/MIT photo)

MAN VEHICLE LABORATORY

The Man Vehicle Laboratory addresses human-vehicle and human-robotic system safety and effectiveness by improving understanding of human physiological and cognitive capabilities. MVL develops countermeasures and display designs to aid pilots, astronauts, 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 Space Shuttle missions, the Mir Space Station, and on many parabolic flights, and developed experiments for the International Space Station.

MVL has five faculty and 20 affiliated graduate students. Research sponsors include NASA, the National Space Biomedical Research Institute, the Office of Naval Research, the Department of Transportation's FAA and FRA, the Center for Integration of Medicine and Innovative Technology, the Deshpande Center, and the MIT Portugal Program. Space projects focus on 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. New major projects include a collaborative study with Draper Laboratory on manual and supervisory control of lunar/planetary landings, and a study of fatigue effects on space teleoperation performance, in collaboration with colleagues at the Brigham and Women's Hospital. Non-

aerospace projects include performance and fatigue effects in locomotive engineers, and advanced helmet designs for brain protection in sports and against explosive blasts. The laboratory also collaborates with the Volpe Transportation Research Center and the Jenks Vestibular Physiology Laboratory of the Massachusetts Eye and Ear Infirmary.

This past year, MVL faculty and graduate students took lead roles in the MIT 150th anniversary celebration's Exploration Symposium. The laboratory's "Bioastronautics Journal Seminar" enrolled 18 graduate students. For the eighth time, MVL MIT Independent Activities Period activities included a popular course on Boeing 767 Systems and Automation and Aircraft Accident Investigation, co-taught with B.N. Nield, Boeing's chief engineer for Aviation Systems Safety.

MVL faculty include Charles Oman (director), Jeffrey Hoffman, Dava Newman, Laurence Young, and Julie Shah. They teach subjects in human factors engineering, space systems engineering, real-time systems and software, space policy, flight simulation, space physiology, aerospace biomedical engineering, the physiology of human spatial orientation, 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), NSBRI Sensory-Motor Adaptation Team (Oman), the MIT-Volpe Program in Transportation Human Factors (Oman), and the MIT Portugal Program's Bioengineering Systems focus area (Newman).

Visit the Man Vehicle Laboratory at <http://mvl.mit.edu/>

THE PARTNERSHIP FOR AIR TRANSPORTATION NOISE AND EMISSIONS REDUCTION

The Partnership for Air Transportation Noise and Emissions Reduction is an MIT-led FAA Center of Excellence sponsored by the FAA, NASA, Transport Canada, the US Department of Defense, and the Environmental Protection Agency. PARTNER research addresses environmental challenges facing aviation through analyzing community noise and emission impacts on climate and air quality. PARTNER also studies a range of environmental impact potential mitigation options including aircraft technologies, fuels, operational procedures, and policies. PARTNER combines the talents of 12 universities, five government agencies, and more than 50 advisory board members, the latter spanning a range of interests from local government, to industry, to citizens' community groups.

MIT's most prominent research role within PARTNER is in analyzing environmental impacts and developing research tools that provide rigorous guidance to policymakers who must decide among alternatives to address aviation's environmental impact. The MIT researchers collaborate with an international team in developing aircraft-level and aviation system level tools to assess the costs and benefits of different policies and mitigation options.

Other PARTNER initiatives in which MIT participates include estimating the lifecycle impacts of alternative fuels for aircraft; studies of aircraft particulate matter microphysics and chemistry; and economic analysis of policies. PARTNER's most recent reports emanating from MIT research are "The Impact of Climate Policy on US Aviation," (with the MIT Joint Program on the Science and Policy of Global Change), and "Assessment of CO₂ Emission

Metrics for a Commercial Aircraft Certification Requirement.” (with the Georgia Institute of Technology). These may be downloaded at <http://web.mit.edu/aeroastro/partner/reports>.

PARTNER MIT personnel include Ian Waitz (director), James Hileman (associate director), Hamsa Balakrishnan, Steven Barrett, John Hansman, Thomas Reynolds, Karen Willcox, William Litant (communications director), Jennifer Leith (program coordinator), and 15-20 graduate students and post docs.

Visit the Partnership for AiR Transportation Noise and Emissions Reduction at <http://www.partner.aero>

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 thrusters and plumes, and their interaction with spacecraft; numerical and experimental models of magnetic cusped thrusters; and space electrodynamic tethers, including their use as antennas for launching electromagnetic waves to remove high-energy particles from earth's Van Allen radiation belts. SPL students also work on ultra-fast (nanosecond) high voltage discharges to trigger combustion reactions and eventually reduce aircraft engine pollution. SPL also has a significant role in designing and building micropropulsion electrospray

thrusters. In addition to providing efficient propulsion for very small satellites in the 1 kg category (such as CubeSats), such engines will enable distributed propulsion for the control of large space structures, like deformable mirrors and apertures. SPL facilities include a supercomputer cluster where plasma and molecular dynamics codes are routinely executed and a state-of-the-art laboratory including three vacuum chambers, clean room environment benches, electron microscope and electronic diagnostic tools to support ongoing research efforts.

Manuel Martinez-Sanchez directs the SPL. Paulo Lozano is the associate director.

Visit the Space Propulsion Laboratory at <http://web.mit.edu/dept/aeroastro/labs/SPL/home.htm>

SPACE SYSTEMS LABORATORY

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, precision optical systems for space telescopes, microgravity experiments operated aboard the International Space Station, and leading the AeroAstro efforts on student-built small satellites. Research encompasses an array of topics that comprise a majority of space systems: systems architecting, dynamics and control, active structural control, thermal analysis, space power and propulsion, microelectromechanical systems, modular space systems design, micro-satellite design, real-time embedded systems, and software development.

Major SSL initiatives study the development of formation flight technology. Significant research has been conducted using the Synchronized Position Hold Engage and Reorient

Experimental Satellites (SPHERES) facility, in the areas of distributed satellites systems, including telescope formation flight, docking, and reconfiguration. The SPHERES facility consists of three small satellites 20 centimeters in diameter that have flown inside the International Space Station since May 2006. They are used to test advanced control software in support of future space missions that require autonomous inspection, docking, assembly and precision formation flight. Over the past four years SSL has successfully completed 21 test sessions with eight astronauts. In 2009 we expanded the uses of SPHERES to include STEM outreach. In the fall of 2009 we began an exciting program called “Zero Robotics” to engage High School students in a competition aboard the ISS using SPHERES. In December 2010 ten students from two Idaho schools came to MIT and saw their algorithms compete against each other in a live feed from the ISS. We look forward to expanding this competition to a national scale.

SSL is in the third year of the SEA program; the Space Engineering Academy immerses junior Air Force officers in the actual development of flight hardware providing first hand experience in implementing best (and avoiding worst) practices in space system procurement. It is a two year, end-to-end, flight-worthy satellite conceive, design, build, integrate, test, and operate program. The SEA students, together with several other SSL graduate assistants, formed a robust group of teaching assistants for the 16.83 capstone satellite design-build course. This year the course tackled two projects: the MIT Satellite team entry to the University Nanosatellite Program and conceptual design of the Exo-Planet cubesat to detect planets in other solar systems. The UNP entry, named CASTOR, is being developed jointly with the Space Propulsion Laboratory to demonstrate an innovative electric thruster. The pro-

pulsion system will be demonstrated in LEO with up to 1 km/s delta-V; if successful a 2 km/s delta-V spacecraft could be built to reach the moon! The Exo-Planet spacecraft is a cooperation between the SSL and faculty in EAPS and the Kavli Institute; it uses an innovative sensor with staged control to detect the presence of planets as they orbit around their stars.

The Electromagnetic Formation Flight testbed is a proof-of-concept demonstration for a formation flight system that has no consumables; a space-qualified version is under study. The MOST project completed architectural studies for lightweight segmented mirror space telescopes using active structural control. Multiple programs research the synthesis and analysis of architectural options for future manned and robotic exploration of the Earth-Moon-Mars system.

SSL continues to lead the development of methodologies and tools for space logistics. Jointly with Aurora Flight Sciences, SSL is developing prototypes for automated asset tracking and management systems for ISS based on radio frequency identification technology. Together with the Jet Propulsion Laboratory, SSL is editing a new AIAA Progress in Aeronautics and Astronautics Volume on Space Logistics that summarizes the current state of the art and future directions in the field.

SSL personnel include David W. Miller (director), Olivier de Weck, Jeffrey Hoffman, Edward F. Crawley, Daniel Hastings, Annalisa Weigel, Manuel Martinez-Sanchez, Paulo Lozano, Alvar Saenz-Otero, Paul Bauer (research specialist), Marilyn E. Good (administrative assistant)

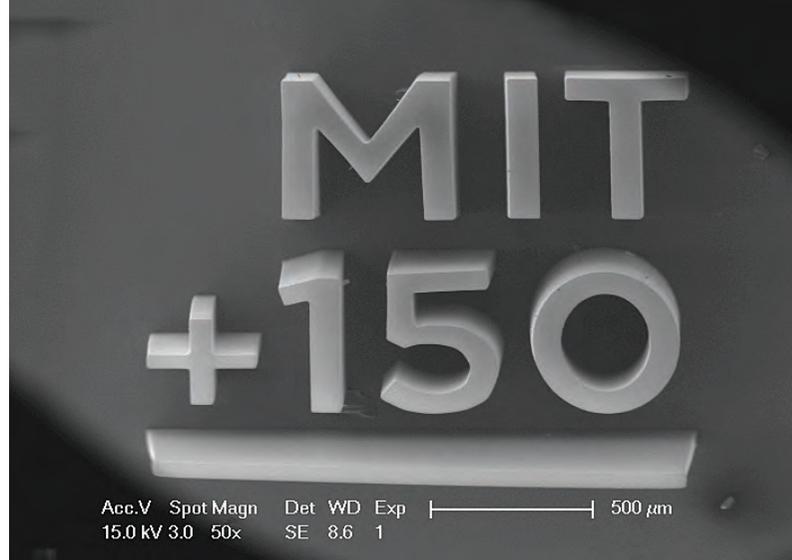
Visit the Space Systems Laboratory at <http://ssl.mit.edu/>

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 advanced structural applications and devices.

TELAMS has broadened its interests from a strong historical background in composite materials, and this is reflected in the name change from the former Technology Laboratory for Advanced Composites. A significant initiative involves engineering materials systems at the nanoscale, particularly focusing on aligned carbon nanotubes as a constituent in new materials and structures. This initiative is in partnership with industry through the Nano-Engineered Composite aerospace STructures Consortium founded at MIT in 2007. Thus, the research interests and ongoing work in the laboratory represent a diverse and growing set of areas and associations. Areas of interest include:

- » nano-engineered hybrid advanced composite design, fabrication, and testing
- » fundamental investigations of mechanical and transport properties of polymer nanocomposites
- » characterization of carbon nanotube bulk engineering properties
- » carbon nanotube synthesis and catalyst development
- » composite tubular structural and laminate failures
- » MEMS-scale mechanical energy harvesting modeling, design, and testing



Aligned carbon nanotubes organized as the MIT 150th anniversary logo via photolithography and then grown in Professor Brian Wardle's Nano-Engineered Composite aerospace STructures (NECST) Consortium lab. Actual size is about 1.5mm. (Namiko Yamamoto/MIT image courtesy Brian L. Wardle's NECST group)

- » 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 length scale 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 and other materials. A recent addition includes several reactors for synthesizing carbon nanotubes. 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 nano and microscopic inspection, nondestructive inspection, high-fidelity characterization of MEMS materials and devices, and a laser vibrometer for dynamic device and structural characterization.

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. This commitment is exemplified in the newly formed NECST Consortium, an industry-supported center for developing hybrid advanced polymeric composites. In all these efforts, the laboratory and its members continue their extensive collaborations with industry, government organizations, other academic institutions, and other groups and faculty within the MIT community.

TELAMS faculty include Paul A. Lagacé, Brian L. Wardle, John Dugundji (emeritus), and visitors Antonio Miravete, Desiree Plata, and Junichiro Shiomi.

Visit the Technology Laboratory for Advanced Materials and Structures at <http://web.mit.edu/telams/> and the Nano-Engineered Composite aerospace Structures Consortium at <http://necst.mit.edu>

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.

Lab director Moe Win and a team of undergraduate and graduate students competed in the Institute of Soldier Nanotechnologies Soldier Design Competition. In this contest they demonstrated the first cooperative location-

aware network for GPS-denied environments, using ultra-wideband technology, leading to the team winning the L3 Communications Prize. They are now advancing the localization algorithms in terms of scalability, robustness to failure, and tracking accuracy.

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.

Moe Win directs the Wireless Communication and Network Sciences Group.

Visit the Wireless Communication and Network Sciences Group at <http://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 w 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 more than 70 years of operations, Wright Brothers Wind Tunnel work has been recorded in hundreds of theses and more than 1,000 technical reports.

WBWT faculty and staff include Mark Drela and Richard Perdichizzi.

Visit the Wright Brothers Wind Tunnel at
<http://web.mit.edu/aeroastro/labs/wbwt/index.html>

CONTRIBUTORS TO THIS ISSUE

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Richard Dahl is a journalist and freelance writer, and a frequent contributor to AeroAstro. He may be reached at cdahl16@gmail.com

Emilio Frazzoli is an associate professor in the MIT Aeronautics and Astronautics Department. Previously, he was an officer in the Italian Navy, a spacecraft dynamics specialist at Telespazio S.p.A. in Rome and a faculty member at the University of Illinois at Urbana Champaign and at the University of California, Los Angeles. His main research interests are aerospace control systems, autonomous air/space/ground vehicles, mobile robotics and transportation networks. Emilio Frazzoli may be reached at frazzoli@mit.edu.

Jonathan P. How is the MIT Richard Cockburn Maclaurin Professor of Aeronautics and Astronautics. Prior to joining the MIT faculty in 2000, he was an assistant professor in the Department of Aeronautics and Astronautics at Stanford University. Research interests in the design and implementation of distributed robust planning algorithms to coordinate multiple autonomous air/ground/space vehicles in dynamic uncertain environments. Jon How may be reached at jhow@mit.edu.

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Brian Williams is a professor and the undergraduate officer in the MIT Aeronautics and Astronautics Department where he leads the Model-based Embedded and Robotic Systems group. His research interests include space and aerial robotics, cognitive robotics, automated reasoning and artificial intelligence, automation for operations and design, hybrid control systems, robot coordination, and energy management. Brian Williams may be reached at williams@mit.edu.

