OUR FUTURE

AERO-ASTRO

STRATEGIC REPORT 2007

Massachusetts
Institute of
Technology

COVER: EARTH AND SUNRISE. PHOTO ILLUSTRATION BY RISTESKI GOCE

OUR FUTURE

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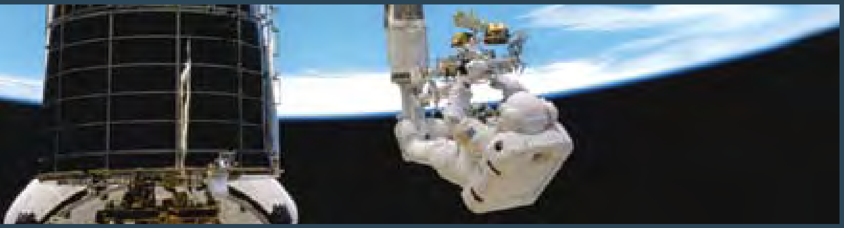
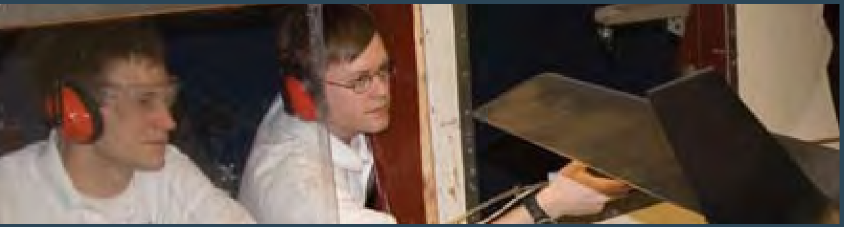
STRATEGIC REPORT 2007





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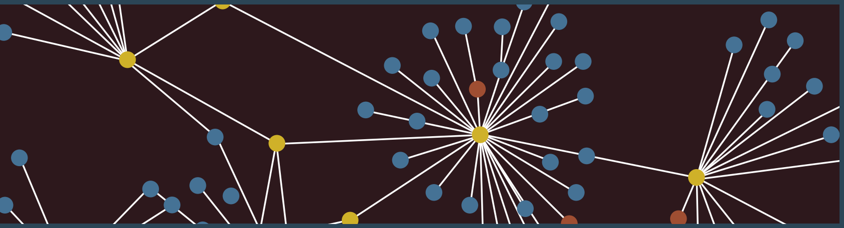


AERO-ASTRO

OUR FUTURE

During 2005-2007, the MIT Department of Aeronautics and Astronautics reviewed, revised, and reinvigorated our strategy, and we developed a new plan for leadership and success. The result is contained in this document.

We start by defining our vision, mission, and goals. We then present our values — the principles and qualities to which we collectively aspire. Next, we review the changes that have occurred in our department during the last 10 years, and describe a *new Department of Aeronautics and Astronautics*, one that is focused on three areas: aerospace vehicle engineering, engineering of large-scale, complex aerospace systems, and aerospace information engineering. Leadership and excellence in these three areas are critical for producing scientific, industrial, and societal advances in the four domains in which we work: transportation, exploration, communication, and national security.

> This document provides a foundation and a roadmap for the future of our department. These are the things that inspire us.

With this as a foundation, we describe eight areas of research and education that present both grand challenges and grand opportunities for aerospace, for the nation, and for the world. These eight areas define not only the present, but, more importantly, the future of our department. We will build and strengthen our capabilities so that we can continue to contribute to these complex multidisciplinary problems. The eight opportunities are:

- space exploration
- autonomous, real-time, humans-in-the-loop systems
- aviation environment and energy
- aerospace communications and networks
- aerospace computation, design and simulation
- air transportation
- fielding of large-scale complex systems
- advancing engineering education

Our ability to address the challenges and opportunities in these areas is multiplied by linkages we have developed within our department, across the Institute, and around the world. We provide evidence of this — we are internally and externally linked in a way that extends our reach, multiplies our talents, and enables us to lead and have impacts on research and education that go well beyond Building 33 in Cambridge, Massachusetts.

In sum, this document provides a foundation and a roadmap for the future of our department. These are the things that inspire us.

Astronauts Jeffrey A. Hoffman (inside the Shuttle bay), now an Aero-Astro Professor of the Practice, and Story Musgrave service the ailing Hubble Space Telescope in December 1993. An accomplished astrophysicist, Hoffman teaches space systems design and space policy. (NASA)

VISION MISSION GOALS

OUR VISION

Aerospace is an exciting, intellectually challenging, and economically important field that offers unique opportunities for students and researchers to contribute to the future of transportation, communication, exploration, and national security.

OUR MISSION

Our mission is to prepare engineers for success and leadership in the conception, design, implementation, and operation of aerospace and related engineering systems. We achieve this through our commitment to educational excellence, and to the creation, development, and application of the technologies critical to aerospace vehicle and information engineering, and to the architecture and engineering of complex high-performance systems.

OUR GOALS

- Educate tomorrow's leaders through innovative educational programs and pedagogies, which have as their context the conception, design, implementation, and operation of systems and processes.
- Create research opportunities that generate inventions, technologies, and solutions to contemporary aerospace problems, in cooperation with colleagues at MIT and other universities, industry, and government, in the United States and abroad.
- Provide leadership to the Institute, and to the national and international aerospace communities.

THE JIM MAR TEST

James Mar, MIT Aero-Astro Department Head from 1981 to 1983, had a simple test that he applied to judge the love of aerospace held by potential faculty members. He would ask "When they are walking across a parking lot and an airplane flies over their heads, do they stop and look up?" We still apply this test today. The students, faculty, and staff in our department have a passion for air and space vehicles.

In Aero-Astro's Wright Brothers Wind Tunnel, graduate student Anna Mracek, alumnus Dr. Samuel Schweighart (left), and doctoral candidate Carl Dietrich test a model of a roadable airplane they plan to manufacture. (WILLIAM LITANT)

OUR VALUES

Our values — the principles and qualities to which we aspire:

- We are committed to excellence and leadership in our research and teaching
- We are united by a passion for air and space vehicles, the technologies that enable them, and the missions they fulfill
- We are committed to personal and professional development of our students, faculty, and staff
- We have a deep sense of responsibility to our profession and society, and lead through service at Institute, national, and international levels
- We are committed to open research and education
- We have mutual respect for our colleagues and a strong sense of community

A NEW DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS

Ten years ago, the Department of Aeronautics and Astronautics had 28 faculty members organized around the aerospace disciplines of structures and materials, fluid mechanics, propulsion, controls, humans and automation, and systems. In 1997 we surveyed our stakeholders, analyzed the needs of aerospace and related fields, and identified opportunities for leadership within our industry and within MIT. We then acted strategically to reposition our department, significantly expanding our efforts in real-time, system-critical aerospace computing, control, autonomy and communication engineering, and also in aerospace system architecture and engineering — while simultaneously redefining and maintaining excellence in the core aerospace vehicles engineering disciplines. We also reformed our undergraduate educational program, adopting modern aerospace systems engineering practices as the context for our curriculum and pedagogy.

> **In an academic world not known for rapid change, we have undergone a step-change in the last 10 years. We now have a new Department of Aeronautics and Astronautics.**

In an academic world not known for rapid change, we have undergone a step-change in the last 10 years. We hired 26 faculty members and raised $23 million to reform our undergraduate engineering program and to build new learning environment for our students. We now have a *new Department of Aeronautics and Astronautics*. What will we do next? Much of the remainder of this document focuses on this question. However, before addressing our future, we briefly describe our new department.

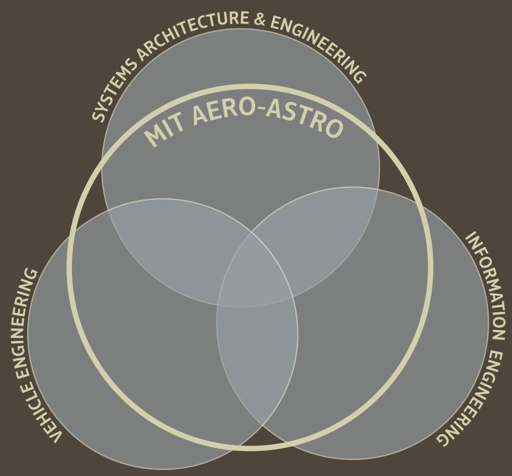
Our department is now organized around three overlapping areas: systems, aerospace information, and vehicles. Each area is populated with between 8 and 15 faculty members.


WILLIAM LITANT

A NEW AERO-ASTRO

The area boundaries are permeable so that substantive research and educational interactions occur across areas. We offer two undergraduate degrees: Aerospace Engineering and Aerospace Engineering with Information Technology. Further, we have gone back to our roots, embracing the modern art of engineering: today, most of our students go through two or three model aerospace system life cycle experiences — conceiving, designing, implementing, and operating — as part of their undergraduate degree program.

We have expanded our linkages with the MIT Department of Electrical Engineering and Computer Science through increased participation in the Laboratory for Information and Decision Systems and the Computer Science and Artificial Intelligence Laboratory. We have expanded our capabilities in the field of engineering systems and now have eight dual appointments with the MIT Engineering Systems Division. We have changed our research and educational activities to address the range of disciplines necessary for leadership in the evolving aerospace industry of today and tomorrow. These include the vehicle disciplines of propulsion and airframes (structures, materials, fluids); the disciplines of real-time systems, autonomy, software, communication, controls and human-machine interaction; and rigorous approaches to the architecture, engineering, implementation, and evolution of complex socio-technical systems. More importantly, as we show later in this document, we have forged effective collaborations among people who practice these disciplines, building teams to enable us to tackle aerospace's most challenging problems.



The **AEROSPACE INFORMATION ENGINEERING** area addresses real-time, safety-critical systems with humans-in-the-loop. Core disciplines within the area are autonomy, software, communications, networks, controls, and human-machine and human-software interaction.

The **AEROSPACE SYSTEMS ENGINEERING** area addresses the increasingly important and cost-sensitive processes that dominate the creation, implementation, and operation of complex socio-technical engineering systems. Core disciplines within this area are system architecture and engineering, simulation and modeling, safety and risk management, policy, economics, and organizational behavior.

The **AEROSPACE VEHICLES ENGINEERING** area addresses the engineering of air and space vehicles, their propulsion systems, and their subsystems. Core disciplines within the area are fluid and solid mechanics, thermodynamics, acoustics, combustion, controls, computation, design, and simulation.

OUR DOMAINS

The Department of Aeronautics and Astronautics contributes to four domains: Exploration, Transportation, Communication, and National Security.

EXPLORATION

On July 20, 1969, the Apollo 11 Lunar Module touched down at Mare Tranquilitatis on the surface of the moon with Aero-Astro Department alumnus Buzz Aldrin and Neil Armstrong on board. Since 1957, 259 manned[1] and 5099 unmanned[2] exploration vehicles have been put into space. The International Space Station has supported a continuous human presence in space since November 2, 2000. The aerospace community has put rovers on Mars, launched the Hubble telescope, and sent probes to explore the solar system. In addition to expanding our knowledge of the universe, the space program has led to hundreds of significant spinoffs ranging from advances in solar power, to improved medical imaging for healthcare, compact microelectronics, better automobile brakes, kidney dialysis machines, cordless power tools, and smoke detectors.[3] Current exploration endeavors include activities to deepen our understanding of the origins of the universe — including plans to send remote rovers and spacecraft to the far reaches of our solar system, the development of a new crewed exploration system by NASA and its contractors, and a national goal to return astronauts to the Moon as a stepping stone to Mars. Further, many of these same technologies are being turned inward to address major problems on our own planet including climate change and resource usage.

JESSICA MARQUES

Professor and former astronaut Jeffrey Hoffman tests a Hamilton-Sundstrand concept space suit at the Haughton-Mars-Project research station on Devon Island in the high Arctic.

TRANSPORTATION


WILLIAM LITANT

Professor and pilot John Hansman studies air transportation systems, air traffic control, human-automation systems, advanced vehicles, and cockpit information systems.

Last year there were 2 billion passenger enplanements and 21 million commercial flights worldwide. At any given time, there are approximately 500,000 people who are in the air. The shipment of cargo by air is a $50 billion industry responsible for 6 percent of the flights and the delivery of 36 percent of the value ($3.25 trillion) of all international freight, enabling decentralized supply chains and global commerce.[4] In the last 30 years, air transportation has grown faster than all other modes of transport, and projections suggest that it will continue to do so for the next 30 years. The market for new commercial aircraft over the next 20 years is estimated at $2.6 to $2.8 trillion.[5] The aerospace industry produces the airplanes and operates the increasingly complex air transportation system that has become integral to our lives, enabling people and goods to move around the world.

At any given time, there are approximately 500,000 people in the air.


CHRIS WELDY

COMMUNICATION

Transatlantic transmission capacity exceeds 5 tera-bits per second (bps), equivalent to 500 million simultaneous voice telephone calls.[6] However, this capacity is not used primarily for voice telephone, but rather for supporting the explosive growth in internet traffic. Over the past decade, the number of internet users has grown from 50 million to more than 1 billion worldwide, and it is expected to exceed 2 billion in just a few years. Satellites play an important role in providing telecommunication services. Today, nearly 30 percent of U.S. households receive television broadcasts via satellite, and the U.S. military heavily relies on satellites in military operations. In 1991, during Operation Desert Storm, the U.S. military had less than 100 mega-bps of satellite transmission capacity available. However, a decade later it was using more than 3 giga-bps of satellite communication capacity. It is projected that approximately 16 giga-bps will be needed to support large military operations by 2010. The aerospace industry contributes to the design, implementation, and operation of communications networks, especially satellite-based networks. Like many other industries, aerospace is increasingly reliant on information technologies and communications. Moreover, since many aerospace systems are safety-critical and require real-time information, they introduce unique performance and quality requirements that challenge today's information engineering capabilities.

Professor Moe Win performs an ultrawide bandwidth signal aggregation experiment. Win is a pioneer of ultrawide bandwidth technology that enables communication and localization in harsh environments.

The aerospace industry contributes to the design, implementation, and operation of communications networks, especially satellite-based networks.

NATIONAL SECURITY

Professor Mary "Missy" Cummings, director of Aero-Astro's Humans and Automation Lab, was one of the Navy's first female fighter pilots.

Aerospace technologies play a critical role in national security, including homeland security. The U.S. Department of Defense currently operates approximately 15,000 piloted vehicles. The capabilities of these vehicles have increased while the number of vehicles has been reduced. Forty-four hour[7] stealth missions have been flown at a range of 14,000 nm by the B-2 bomber, and vehicles like the F-22 are capable of supersonic speed without an afterburner. Launch systems, missiles, and space-based sensing and surveillance capability are also the result of aerospace engineering.

These aerospace systems have not only contributed to national defense, they have produced other impacts as well. For example, civilians around the world depend on the Global Positioning System to navigate automobiles, airplanes, boats, bicycles, and farm equipment; for hiking, surveying, and mapping; and for mobile telephone emergency location services.

We are now entering a new age for national and homeland security. A major change involves the development of unmanned air vehicles (UAVs). The U.S. DoD inventory now includes more than 500 large UAVs and more than 3000 small UAVs (less than 10 lbs).[8] In less than a decade, it is likely the DoD inventory will include more UAVs than piloted vehicles. Projections suggest that the UAV market will be worth more than $50 billion over the next 10 years.[9] There are immense potentials for new capabilities with UAVs, but their use also poses challenges for simultaneous planning, coordination, and control of hundreds of UAVs operating autonomously among, and in conjunction with, ground forces and piloted air vehicles.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EIGHT OPPORTUNITIES THAT WILL DEFINE OUR FUTURE

We have identified eight areas that present grand challenges and grand opportunities for aerospace, for the nation, and for the world. We will build and strengthen Aero-Astro Department capabilities so that we can continue to contribute to these complex multidisciplinary problems.

A Lockheed Martin Atlas 5 lifts from Cape Canaveral on January 19, 2006 bearing the New Horizons spacecraft, which will explore Pluto and the edges of our solar system. (PAT CORKERY/LOCKHEED MARTIN)

Ever since I was 3 years old,
I wanted to be an astronaut.

SPACE EXPLORATION

Each year, we informally survey our entering undergraduate students and find the same result: half of them want to be astronauts. Most go on to develop strong interests in other exciting areas of aerospace, and to pursue other aerospace careers (although, at 34 and counting, MIT has educated more astronauts than any other private institution — only the U.S. Naval Academy has educated more). Nonetheless, our students come to us with a passion for manned space exploration, and, independent of other interests they develop, this interest stays with them. Many of our faculty members have this same interest.

Recently, NASA has refocused its attention on increasing knowledge of the Earth, Moon, and Mars. To enable the new vision, a man-rated launch vehicle, the Ares I, is being designed and built, along with a capsule-based manned spacecraft, the Orion. These systems, and others that will follow them, offer exciting and important opportunities for new contributions, particularly in the areas of space system design and architecture, avionics and software, systems safety, human-machine interaction, and autonomous system operations.

It is hard to imagine an environment more safety critical than one where humans are put 50 million miles from home, in an atmosphere devoid of oxygen, with only 20,000 kg of payload, where it takes 200 days to return, and communications take 30 minutes to reach Earth. Conquering such an environment requires that we answer questions such as: What system designs and architectures should we consider for returning to the Moon and building a lunar outpost? How can systems be developed for lunar exploration, while being extensible to Mars? How can humans and robots work together most effectively in rugged and unknown terrain? How can spacesuits be designed to be more ergonomic, lightweight and resilient to threats such as micrometeorites and tears? How can we characterize the effects of microgravity on the human body and counteract these effects for long-term space flight?

> **50 million miles from home, in an atmosphere devoid of oxygen, with only 20,000 kg of payload, it takes 200 days to return, and communications take 30 minutes to reach Earth.**

MIT Aero-Astro has made major contributions to space exploration in the past, especially as part of the development of the Apollo guidance and navigation system during the 1960s. More recent activities include our NASA Concept Evaluation & Refinement (CE&R) study, conducted jointly with the Draper Laboratory. Eight faculty members and 25 students worked together pioneering the "Mars-back" approach — developing systems primarily for Mars as a basis for developing derivatives for the nearer term lunar missions. Other recent research for NASA headquarters has contributed innovative lunar lander

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configurations, new concepts for modular lunar habitats that have broadened the concepts being considered by NASA's Lunar Architecture Team, and revolutionary approaches to safety engineering and risk management for the space exploration mission that are being used by NASA and its contractors.

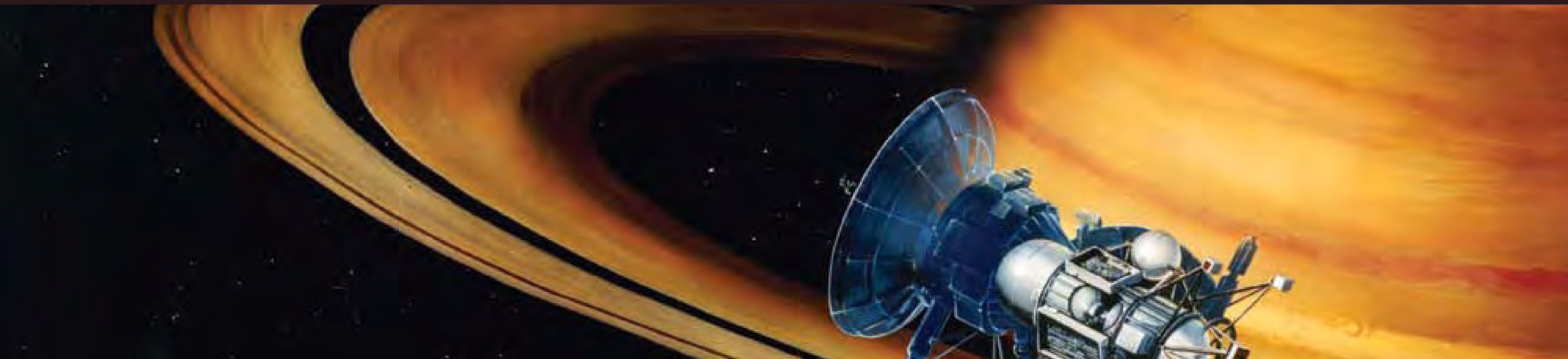

NASA

SPHERES are innovative micro-satellites designed for operations in microgravity by the MIT Space Systems Laboratory in cooperation with Payload Systems Inc. Here, astronaut Jeff Williams is performing autonomous formation flight testing aboard the International Space Station during Expedition 13 in 2006.

We are also leading the development of interplanetary logistics models where space exploration missions are considered as part of an interplanetary supply chain, capturing the flows of vehicles, crews, and cargo in an integrated fashion. We have used these models to understand the optimal mix of pre-positioning, carry-along and resupply flights for a lunar outpost, and to quantify the effects of system reliability, commonality, and reconfigurability on resupply needs. Novel experiments at the Haughton-Mars-Project station on Devon Island in the high Arctic have been used to test and calibrate our models. NASA has adopted our SpaceNet simulation software to reduce the time required to evaluate the feasibility and effectiveness of competing lunar campaigns to minutes, rather than the weeks or months previously required. We were first in quantitatively demonstrating that reconfigurability and commonality of orbital replacement units can save up to 30 percent in spares mass with no loss in system availability for a typical Mars design reference mission.

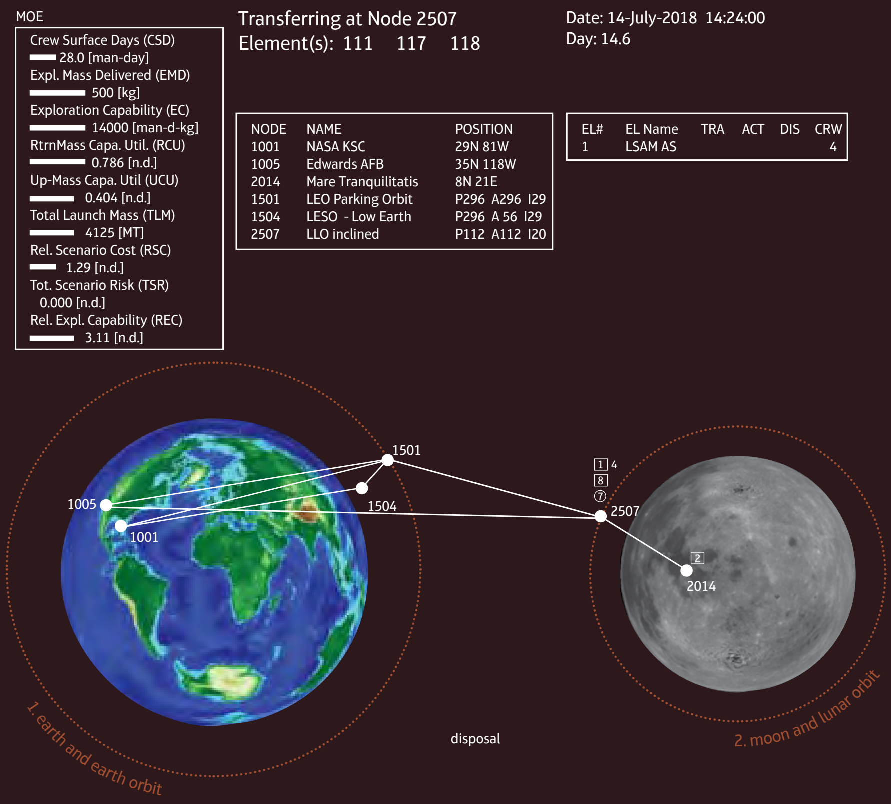
The department is also developing advanced electric propulsion systems where particles are charged by gas or liquid ionization and then accelerated with electromagnetic fields to velocities much greater than with conventional rockets. This has included the design and demonstration of a high efficiency 200 Watt Hall thruster. We have developed silicon liquid-bipropellant micro-rocket engines using microelectronic fabrication processes, demonstrated chip-sized thrust chambers, turbopumps, and valves, and demonstrated more than 1N thrust to date. We have extensively studied the use of these motors as the enabling technology for tiny launch vehicles (80-200kg), extending the definition of low cost access to space to encompass low cost per mission, rather than simply cost per pound. Other revolutionary technologies we

Despite the renewed emphasis on human explorers, robotic surface explorers and remote sensing satellites remain the primary means for gathering scientific knowledge about the Earth, Moon, Mars, and the universe.



have invented are the Electro-Magnetic Formation Flight concept, and a revolutionary spacesuit called BioSuit that provides enhanced astronaut extravehicular activity locomotion and life support.

Despite the renewed emphasis on human explorers, robotic surface explorers and remote sensing satellites remain the primary means for gathering scientific knowledge about the Earth, Moon, Mars, and the universe. Important questions for this endeavor include how can a new generation of space telescopes be designed with aperture sizes that exceed launch vehicle payload faring dimensions and how can arrays of satellites operate collaboratively as interferometers?



MOE

Crew Surface Days (CSD)	28.0 [man-day]
Expl. Mass Delivered (EMD)	500 [kg]
Exploration Capability (EC)	14000 [man-d-kg]
RtrnMass Capa. Util. (RCU)	0.786 [n.d.]
Up-Mass Capa. Util (UCU)	0.404 [n.d.]
Total Launch Mass (TLM)	4125 [MT]
Rel. Scenario Cost (RSC)	1.29 [n.d.]
Tot. Scenario Risk (TSR)	0.000 [n.d.]
Rel. Expl. Capability (REC)	3.11 [n.d.]

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Element(s): 111 117 118

Date: 14-July-2018 14:24:00
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NODE	NAME	POSITION
1001	NASA KSC	29N 81W
1005	Edwards AFB	35N 118W
2014	Mare Tranquilitatis	8N 21E
1501	LEO Parking Orbit	P296 A296 I29
1504	LESO - Low Earth	P296 A 56 I29
2507	LLO inclined	P112 A112 I20

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The SpaceNet 1.3 simulation software was developed by Professor Olivier de Weck and his students along with partners at JPL. This image shows a lunar exploration sortie mission in 2018, capturing the flow of vehicles, crew and cargo including the feasibility and measures of effectiveness predicted for the mission.

To answer these questions, we have led the development of on-orbit microgravity testbeds and satellites. We recently developed guidance, navigation, and control algorithms and a software architecture for fleets of multiple spacecraft that can be used for formation flight, assembly, and docking systems. In tests onboard the International Space Station, the Aero-Astro-developed SPHERES satellite formation flight testbed has demonstrated the performance, predictability, modularity, and ease of interfacing of this architecture. In doing so, we have developed the first documented embedded software validation and verification process for multi-satellite systems, performed the first three and four vehicle precision formation flight in microgravity, performed the first on-orbit docking with a tumbling satellite, and enabled multiple researchers and partner institutions to rapidly and predictably test their component algorithms through the modularity of our architecture. Other research in this area is pushing the envelope in integrated modeling and simulation of large-aperture segmented space, air, and ground telescopes.

Future challenges in space exploration will be met only by thinking “out of the box” and going beyond traditional paradigms and well established technologies. This is one of our strengths. We will work together with our long-term partners in NASA, JPL, other universities, and industry to advance our understanding of the Earth, the Moon, Mars, our solar system, and the universe.

A U.S. Air Force Predator is ready for a night flight from Kandahar Airfield in Afghanistan. Aero-Astro researchers are developing next-generation UAVs featuring flight and autonomous operational capabilities far beyond those of current aircraft.

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AUTONOMOUS, REAL-TIME HUMANS-IN-THE-LOOP SYSTEMS

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 (UGVs and UASs) to execute its missions. The number of flight hours for military UAVs grew from about 1300 hours in 1991 to more than 160,000 hours in 2006.[10] 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, such as firefighting and first-responder missions.

> Challenges exist not only in achieving higher levels of autonomy, but in integrating autonomous operations into systems and in determining the most effective role for humans.

A key feature that characterizes 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 that are in the air over the United States on any given day?

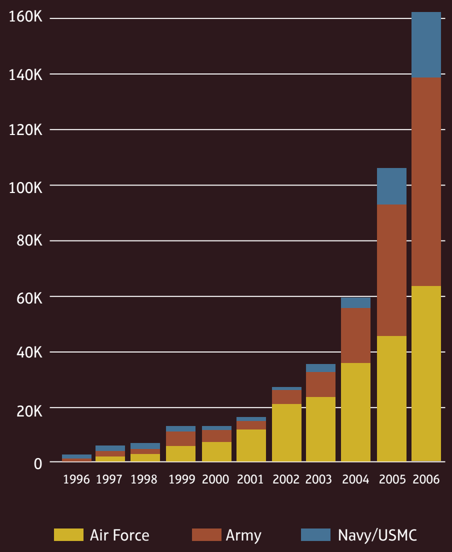
Autonomous systems research is also critical in the design and operation of distributed sensor and communication networks. These networks can combine both static and dynamic nodes using cooperative mobile vehicles. The networks can be used to perform and support the surveillance over a broad area, and thus have significant military and commercial applications.

Department faculty members collaborate extensively with each other and with researchers in Electrical Engineering and Computer Science and Mechanical Engineering on this vibrant research area. They 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.

We have demonstrated fully-autonomous UAV flight in a 5 x 10 meter room and coordinated autonomous flight of 10 vehicles. We invented a way of thinking about combining complicated maneuvers of autonomous vehicles that led to a demonstration of UAV maneuvers that are comparable to the abilities of the best radio-controlled airplane pilots. We have invented methods for model-based autonomy that enable the creation of long-lived autonomous systems able to explore, command, diagnose, and repair themselves using fast, commonsense reasoning. These methods were used on the NASA New Millennium Deep Space One Probe that was launched in 1998 for a 3-year mission. We are now working on methods for intelligently and autonomously mapping unexplored landscapes. Aero-Astro is leading the planning and control team associated with the 2007 DARPA Grand Challenge in collaboration with Mechanical Engineering and EECS, where a fully autonomous car will race against other cars in an urban environment. We are solving critical issues for human supervisory control of complex autonomous systems to define how best to fit the human into these advanced, networked, real-time, safety critical systems.

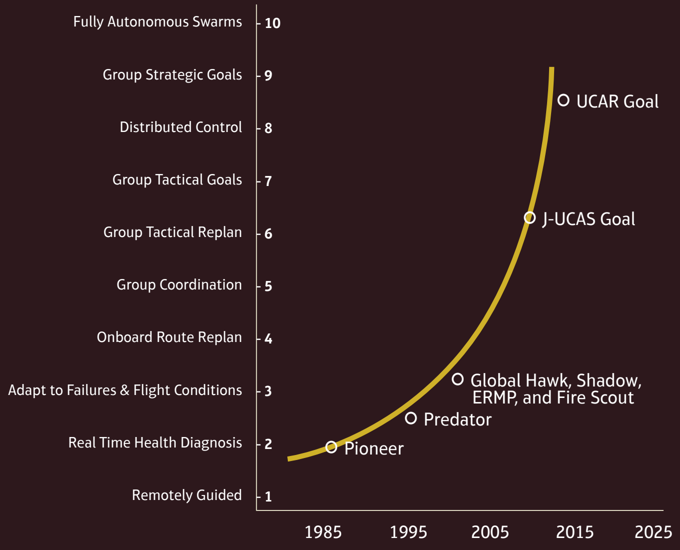
US DOD, UAS ROADMAP 2005

UNMANNED AERIAL VEHICLE FLIGHT HOURS



Growth of flying hours for unmanned air vehicles. (Redrawn from Air Force Magazine, March, 2007)

AUTONOMOUS CONTROL LEVELS



Trend in unmanned air vehicle autonomy. (Redrawn from Figure 4.0-2, US DOD Unmanned Air Systems Roadmap, 2005)

Aero-Astro's Aerospace Control Lab director Professor Jonathan How's work on UAV autonomous planning and control in uncertain environments has great potential for applications such as national security, homeland security, and disaster response.

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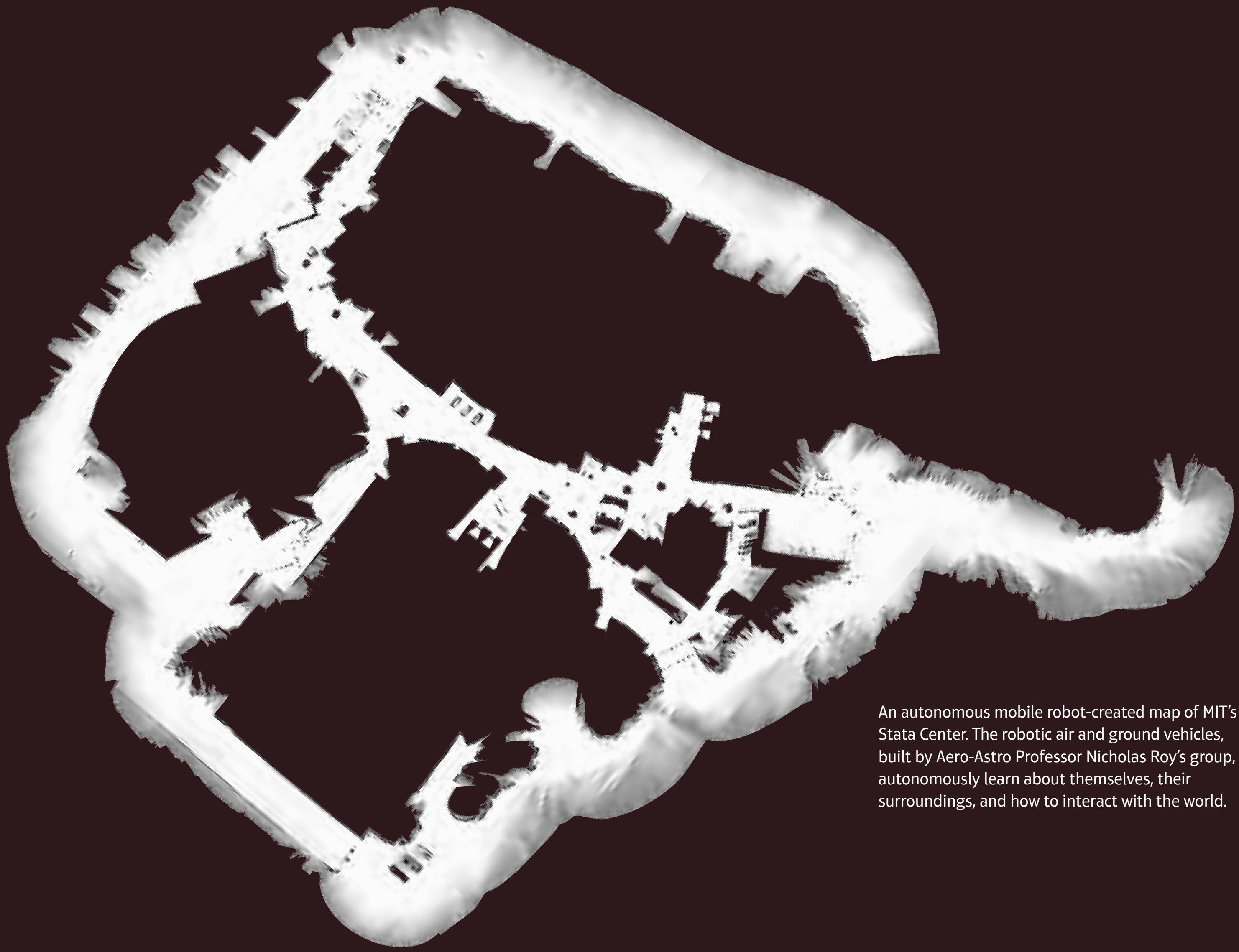

An autonomous mobile robot-created map of MIT's Stata Center. The robotic air and ground vehicles, built by Aero-Astro Professor Nicholas Roy's group, autonomously learn about themselves, their surroundings, and how to interact with the world.

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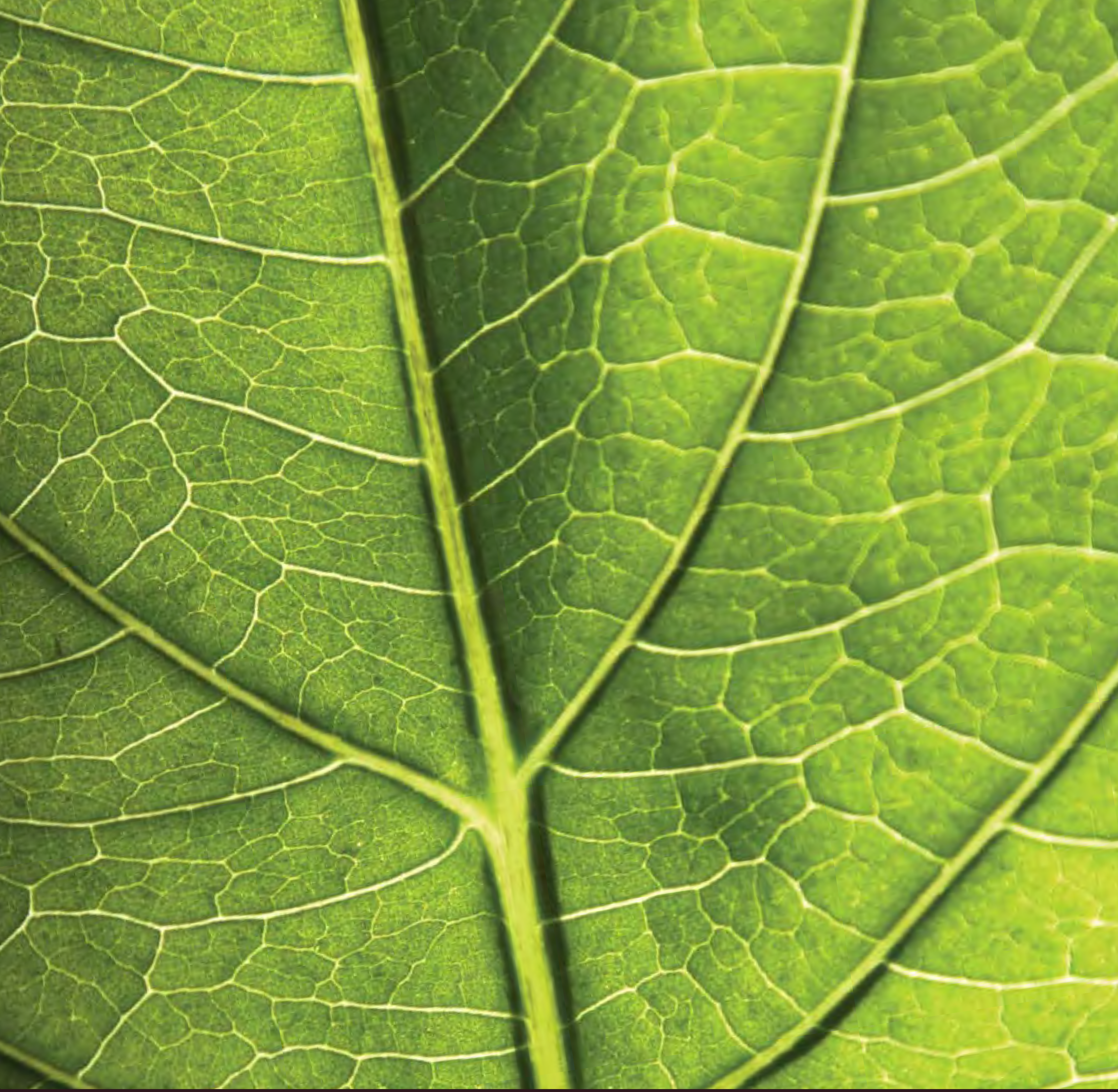

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AVIATION, ENERGY ENVIRONMENT

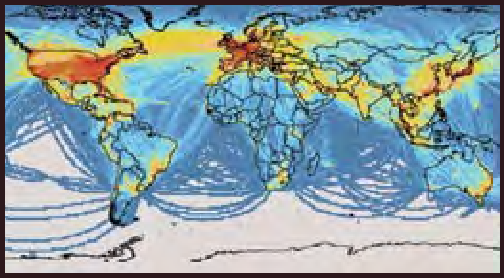
> “Flying — the worst thing to do … The dirtiest industry in the world”
>
> B. SEWILL, *FLY NOW, GRIEVE LATER*, 2005[11]

> “… unrelenting carbon-efficient improvement is business as usual for commercial airlines … We are the greenest form of mass transportation.”
>
> J. C. MAY, *AIR TRANSPORT ASSOCIATION PRESIDENT AND CEO*, CONGRESSIONAL TESTIMONY, 2007[12]

Aviation, environment, and energy: the debate is intense and intensifying. What are the facts? How should we address aviation’s contribution to climate change, local air quality impacts and community noise? Is there a role for alternative fuels for aviation? Do technological and operational solutions exist to reduce aviation’s impacts in absolute terms, notwithstanding growth? What policies should be implemented to best balance economy and mobility, environment, and security? How do we reconcile the contribution that aviation makes to our society and way of life with what we are all taught in kindergarten: clean up your own mess?

MIT is a leader in this complex, rapidly evolving area of aerospace engineering. We lead the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), the FAA/NASA/Transport Canada Center of Excellence with 12 universities, 50 organizations on the advisory board, and linkages throughout the world. On behalf of the U.S. Secretary of Transportation and the NASA Administrator, PARTNER drafted the Report to the U.S. Congress on Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions. The vision calls for absolute reductions in significant impacts notwithstanding anticipated growth, reducing uncertainty regarding aviation's contribution to climate change, particulate matter, and hazardous air pollutants, and greater coordination and communication among stakeholders.

We are leading the development of tools that the U.S. Federal Aviation Administration has committed to use to evaluate the health, welfare, and economic impacts of aviation in order to inform domestic and international policy making. Working with the U.S. DOT Volpe National Transportation Systems Center and the Logistics Management Institute, we developed the tools that the United States uses for reporting its aviation emissions inventories under the United Nations Framework Convention on Climate Change. We designed and flight-tested new arrival procedures that are being implemented around the world to reduce noise, emissions, and fuel burn. We have characterized the fundamental physics and chemistry of aircraft particulate emissions and evaluated their health impacts. With Cambridge University, and a number of industry and government partners, we created the Silent Aircraft Initiative, a collaboration aimed at developing the con-



Distribution of aircraft carbon emissions for 2000 from the FAA System for assessing Aviation's Global Emissions developed by Aero-Astro, US DOT Volpe Center, and the Logistics Management Institute.

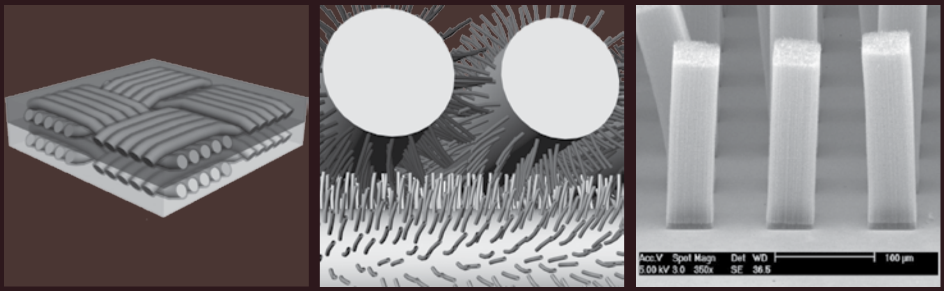
> **"Noise complaints about Logan International Airport exploded during the first six months of the year, with a wave of protests about the roaring jet engines coming from outraged ... residents and politicians."** [13]
>
> **BOSTON HERALD, AUGUST 12, 2007**

> **"In the last 30 years the number of people impacted by aviation noise has been reduced 95% despite a 6-fold growth in people-miles traveled by air."** [14]
>
> **REPORT TO CONGRESS ON AVIATION AND ENVIRONMENT, 2004**

ceptual design of an aircraft that would be inaudible outside the boundary of an urban airport. The technologies and operations conceived for this new, unique aircraft may enable not only a dramatic reduction in aircraft noise, but also a 25 percent reduction in fuel burn compared to current civil engines.

The Aero-Astro/Cambridge University Silent Aircraft Initiative was conceived to make a substantial reduction in aircraft noise. The plane could also reduce fuel consumption by 25 percent compared to current aircraft.

Such improvements in energy efficiency are critical. Although aircraft account for less than three percent of total non-renewable energy usage, their contribution is anticipated to grow. Further, the economics of commercial and military aviation are strongly influenced by fuel availability and price. We are continuing our long-standing efforts to develop energy efficient aircraft and operations, but we have recently expanded these into new areas. We have established a collaboration with the MIT Laboratory for Energy and Environment and a team of international university and industry partners to evaluate the challenges and opportunities for alternative fuels for aviation. We have also formed an aerospace industry consortium to develop a new class of mass-efficient nano-engineered materials which offer efficiency through multi-functionality, and which take advantage of the outstanding mass-specific properties of carbon nanotubes. Many of the technologies we are studying for advancing aircraft propulsion also have direct application in energy systems associated with land-based gas turbine power generation.



Aligned carbon nanotube (CNT) multi-scale hybrid advanced composite architecture developed by Professor Brian Wardle, Dr. Enrique Garcia, and colleagues, as part of MIT's Nano-engineered Composite aerospace STructures (NECST) Consortium: (left) illustration of woven fabric with in situ grown CNTs, (middle) illustration of aligned CNTs on fabric fibers, and (right) scanning electron micrograph of aligned CNT pillars. There are 10-100 billion aligned CNTs per square centimeter.

In sum, dozens of MIT Aero-Astro students, researchers, and faculty members are engaged in advancing the science, policy, economic, and engineering aspects relating to the interaction of aviation, environment, and energy. The department is seizing the opportunities to replace rhetoric with scientific and engineering analyses and rational judgment, to invent and implement new technologies and operations for vehicles and the air transportation system, and, thereby, to advance a sustainable aviation system that contributes to the betterment of society in all dimensions of economy and mobility, environment, and national security.

04

AEROSPACE COMMUNICATIONS AND NETWORKS

Communication technology is integral to most aerospace systems. Communication satellites bring us live coverage of events from around the world, deep-space communication links offer vivid images from outer space, and aircraft rely on communications for command and control. In many locations lacking terrestrial communication infrastructure, satellite-based networks provide the only viable mechanism for vital communication services. For example, the U.S. military depends on satellites for rapidly deployable, robust, and reliable communications during military operations, and satellites are often the only available means of communications for disaster relief operations, such as the December 2005 tsunami or 2006's Hurricane Katrina.

Current communications satellites were designed as stand-alone systems, almost exclusively for supporting voice and video traffic. They are inefficient for the transmission of internet data traffic, which, unlike voice and video, tends to occur in bursts and to require greater reliability (there is less tolerance for transmission errors). These inefficiencies are exacerbated by the unique characteristics of the satellite channel: high bit error rates and high latency for signal propagation to and from the satellite. Consequently, current satellite systems may only be able to utilize 10 percent of their capacity when used for the transmission of internet traffic.

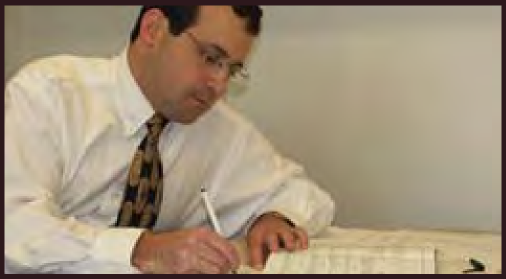
> **Current satellite systems may only be able to utilize 10 percent of their capacity when used for the transmission of internet traffic.**

Department faculty members play a major role in designing future aerospace communication networks; for example, in leading the paradigm shift from circuit-based to packet-based communications systems for future military satellites. Faculty members have also made pioneering contributions to the development of ultra-wide band communication technology that enables accurate ranging, position location and reliable transmission in a harsh multi-path environment (for example, in and around buildings).

Many challenges remain in the design of future aerospace communication networks for both military and civilian use. In recent years, the U.S. military has embarked on a transformation of the space network architecture into a packet-based system much like the internet. There are important issues to be resolved concerning design of next generation packet processing satellite networks, including resource allocation algorithms, efficient protocols, space-ground network architectures and interfaces, and protocols

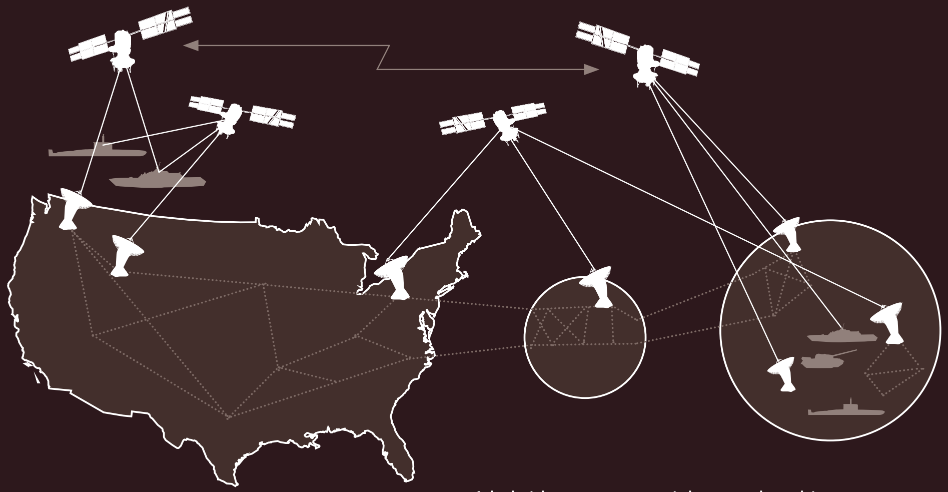
04

for inter-networking space and terrestrial networks. Moreover, communication technology is also core to NASA space exploration missions to the Moon, Mars, and beyond. To enable the delivery of high definition video and science data from space, transmission capacity must be increased by two to three orders of magnitude beyond what is possible with current technology. Doing this will require breakthrough developments in transmission technology, resource allocation algorithms, and efficient protocol designs. Further, both the U.S. military and NASA increasingly rely on autonomous air and ground vehicles. These systems depend on cooperative control among mobile vehicles and, consequently, on the availability of a communications capability among the vehicles. Developing a communication system for autonomous vehicles is a daunting task due to the mobility of the nodes, the need to make efficient use of resources (such as energy), and the lack of centralized control.



WILLIAM LITANT

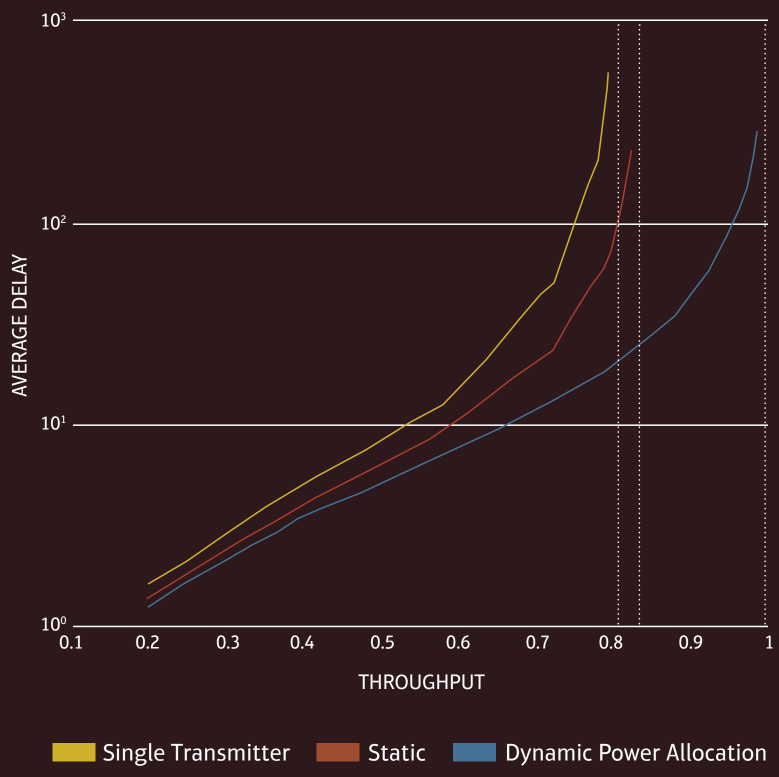
Professor Eytan Modiano's Aero-Astro Communications and Networking Research Group is designing protocols for networks that include both earthbound and orbiting components.



A hybrid space-terrestrial network architecture including optical and wireless terrestrial networks, satellite links, and optical space links.

REDRAWN BASED ON MIT LINCOLN LABORATORY ORIGINAL ARTWORK

AVERAGE PACKET DELAY FOR THREE POWER ALLOCATION ALGORITHMS



This plot demonstrates the improvement in throughput and delay resulting from an optimal dynamic power allocation algorithm for multi-beam satellites, developed by Professor Eytan Modiano and his students.

Professors Jaime Peraire and Mark Drela, and research scientist David Willis, are numerically simulating bat flight. Their collaboration with colleagues at Brown University on this topic may advance the design of highly maneuverable UAVs.

AEROSPACE
COMPUTATION
DESIGN & SIMULATION

Computation for simulation and optimization is essential to the design and operation of aerospace systems. For example, for its 787 program, Boeing credits computational engineering for requiring the building and testing of only seven prototype wings, compared to the 77 wings required for its predecessor, the 767.[16] Some engine design changes are now certified for flight safety based on simulations alone. Revenues from simulation and optimization software products are estimated to be in the billions of dollars, and the overall economic impact of these products is in the trillions of dollars.[17]

Despite these advances, there is consensus in the academic and institutional community that the field of computational science and engineering has yet to provide its full potential. As an illustration, consider digital flight: the modeling of aircraft aerodynamics throughout the entire flight envelope. Current high-fidelity computational fluid dynamics simulations are only reliable in on-design conditions (such as cruise) and for "standard" aircraft configurations. As a result, CFD is used for only a small number of operating points, while a combination of wind-tunnel experiments and low-fidelity models must be employed for the majority of flight conditions. In 10 to 15 years there will exist sufficient raw computational power to allow analysis of an aircraft's entire flight envelope using high-fidelity CFD. However, unless the reliability and automation of these methods is improved, accurate prediction of performance in all critical regions of the flight envelope will remain insurmountable. To address these challenges our department is leading the development of a new generation of flow solvers that represent a step change in both fidelity and automation. NASA, Boeing, and the U.S. Air Force are adopting preliminary versions of these codes.

> **"Formidable challenges stand in the way of progress in simulation-based engineering science research."**
>
> NATIONAL SCIENCE FOUNDATION, 2006[15]

Ultimately, we must develop multidisciplinary simulation capabilities that include not only aerodynamic simulations, but also high-fidelity structural analyses, dynamics and control, and environmental performance. A grand challenge is incorporating these elements into a design and optimization setting that is also able to address the effects of uncertainties in modeling, operation, parameters, and requirements.

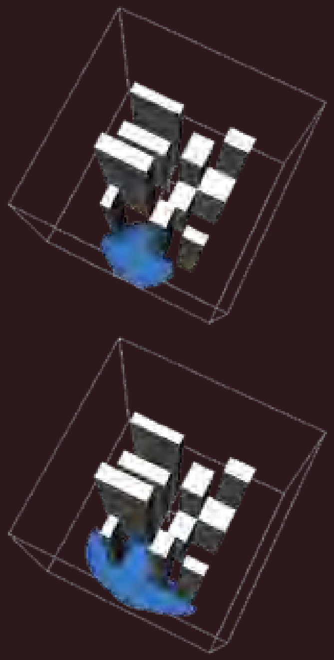
Multiscale materials modeling is another area of focus for the department. Because the connection between material microstructure and performance characteristics such as

05

yield strength and ductility is generally unknown, material design has been based largely on empiricism. Multiscale materials modeling combined with high-performance computation provides a rational approach to material design. We are leading the application of this modeling paradigm to a variety of problems, for example, explaining the anomalous strength and ductility behavior of novel nano-structured metals. We have also been able to predict, for the first time, macroscopic material behavior, such as aluminum surface roughening in the forming process.

The department is also a leader in the analysis of blast effects on structures and humans and the conceptual design of blast-protective structures. As of March 2007, two-thirds of the 24,000 battlefield injuries suffered by soldiers in Iraq and Afghanistan were from bombs, and of these, 28 percent involved brain trauma.[18] We have developed a computational framework for understanding the injurious effects of blast waves on the human brain. The framework includes coupled blast-solid interaction analysis methods, tissue models, and high-fidelity anatomical models of the human head, and was developed in collaboration with the Defense and Veterans Brain Injury Center at the Walter Reed Army Medical Command. This capability is now being used to define the underlying mechanisms leading to brain injury and to develop injury mitigation strategies.

We are also making advances in real-time simulations — those performed at timescales less than the timescales of the physical problem. A challenge with applications to homeland security is to solve an inverse contaminant transport problem in an urban area represented by a grid of millions of cells, with limited measurements, in order to determine the probable upstream source of a contaminant release, and the

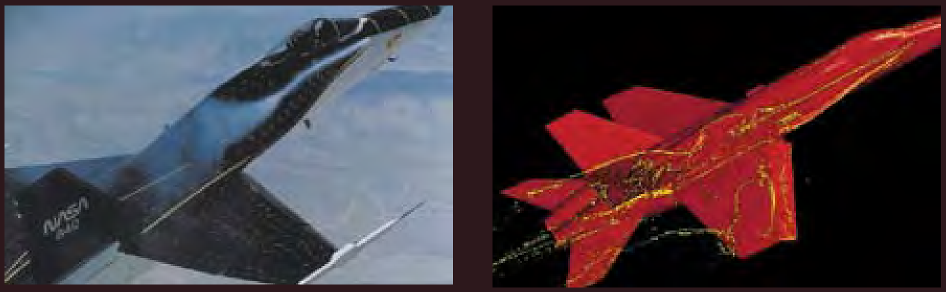


Field simulations of contaminant transport through complex domains take only seconds, using reduced-order models developed by Aero-Astro Professor Karen Willcox.

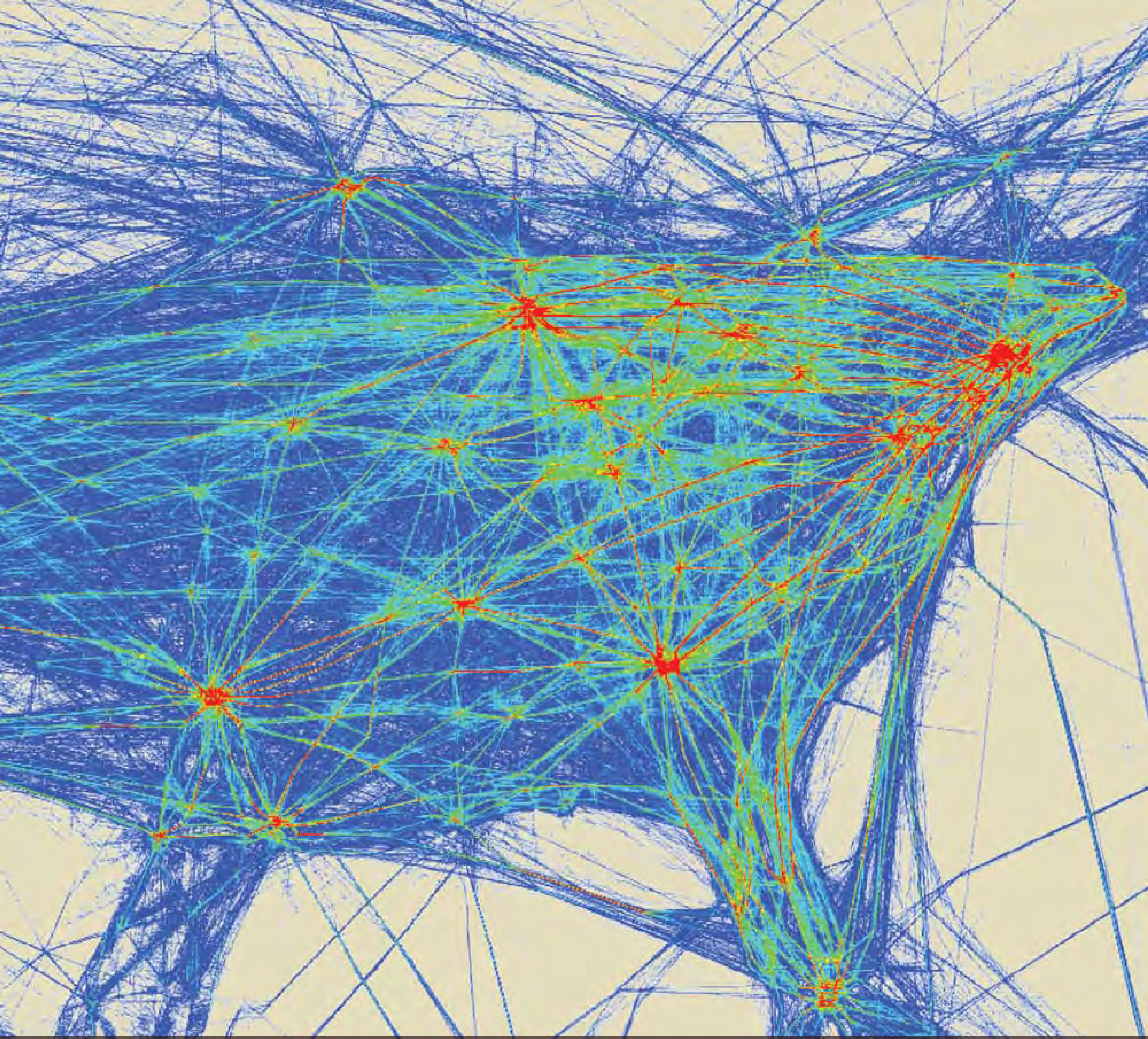
Incorporating these elements into a design and optimization setting that is also able to address the effects of uncertainties in modeling, operation, parameters, and requirements is a grand challenge.

Aero-Astro Aerospace Computational Design Laboratory students develop and use computational methods to study a range of problems. (WILLIAM LITANT)

potential downstream impact areas. This all must occur within a few minutes, to allow for emergency response. We are developing approaches to model reduction that enable the creation of accurate models that achieve these demanding real-time goals. Deployment of such methods in a practical setting means developing the ability to incorporate multidisciplinary models, quantify uncertainties, and achieve robust decision-making under conditions of uncertainty.



A flight test of the F/A-18 shows the dispersion of smoke particles that results from a vortex burst (left). Automatic identification and visualization of vortex cores, developed by Aero-Astro's Robert Haimes and Dr. David Kenwright of NASA Ames, reveal the same behavior in a CFD simulation (right). Visualization software developed by Haimes is used throughout the world.



A typical 24 hours in the eastern United States shown on a density map of flights on January 22, 2004. The busiest regions have more than 100 flights per square kilometer. (MIT INTERNATIONAL CENTER FOR AIR TRANSPORTATION DOCTORAL STUDENT ALEKSANDRA MOZDZANOWSKA)

AIR TRANSPORTATION

The air transportation system is an enabler of global trade and travel. It has been estimated that the commercial aviation industry contributes 8 percent of the U.S. gross domestic product.[19] The U.S. air transportation system is the safest in the world, with 22 safety-related fatalities per year[20] (on average for the last four years) despite approximately 700 million U.S. enplanements per year.[21] However, the expansion from 2700 aircraft and 14,000 flights per day in the United States in 1970, to 8200 aircraft and 31,000 flights per day in 2006[22,23] has posed several challenges, which are likely to worsen with the two- to three-fold increase in air traffic projected by the year 2025.

> The system is approaching capacity limits at major airports and flight corridors; small delays result in nonlinear increases in system-wide impacts.

The air transportation system is approaching capacity limits at major airports and flight corridors. Due to the highly integrated nature of the network, small delays result in nonlinear increases in system-wide impacts. This is evidenced by the increasing volatility of delays in the National Airspace System, most of which are caused by weather. Recent news reports have highlighted the situation: on December 21, 2006, more than 1300 flights were delayed due to weather, stranding thousands of people; on June 20, 2007 there were more than 800 delayed flights, 77 cancellations, and a complete shutdown of one airline's operations for two hours due to a computer failure.[24] In 2006, there was a record-high of 22 million minutes of delays in the United States.[25]

Enhancing system capacity to satisfy the predicted demand is a difficult problem, confounded by the legacy systems and procedures developed over the past 60 years. System upgrades or redesign of procedures to improve efficiency cannot degrade the high level of safety and must be shown to have minimal environmental impact before they can gain acceptance from policy-makers and the public. Security is an additional constraint that has gained more importance since 9/11. The air transportation infrastructure is a complex, dynamic, socio-technical system; to address the major issues requires collaboration among researchers in systems engineering, navigation, communication, dynamics and control, human supervisory control, environmental impact modeling, economics, operations research, and technology and policy.

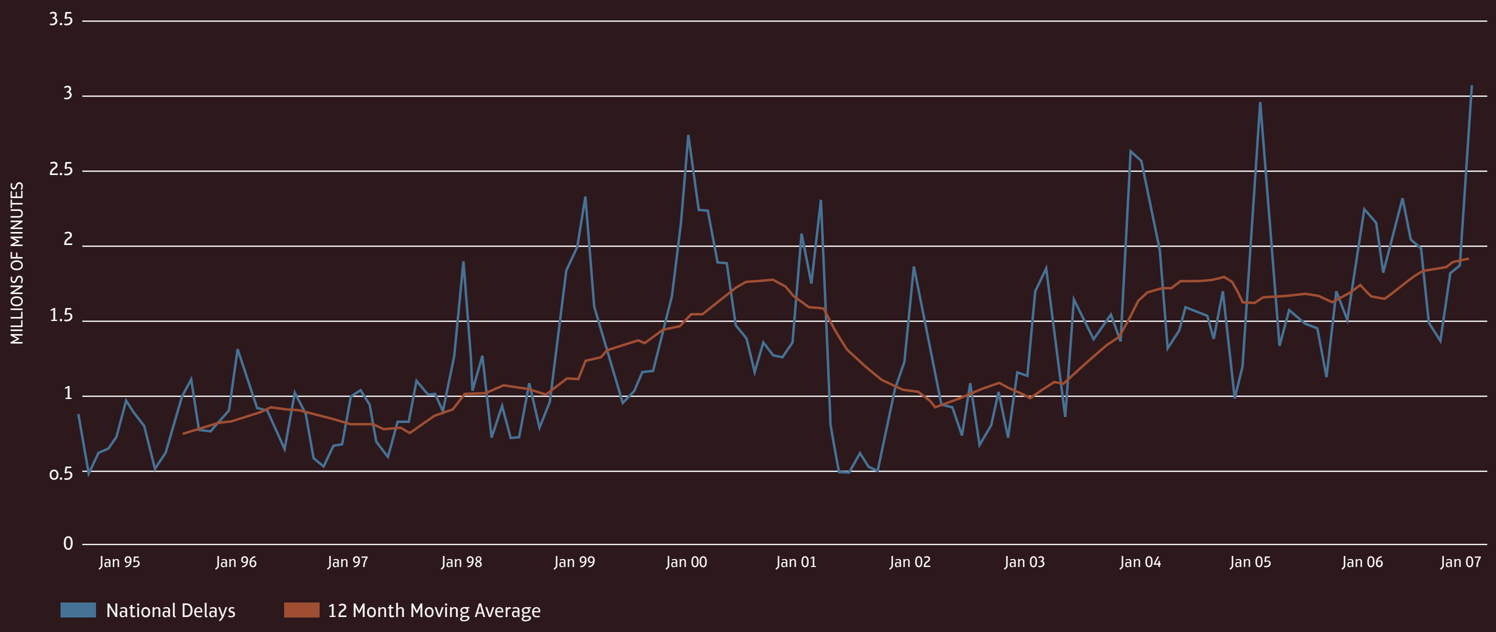
06

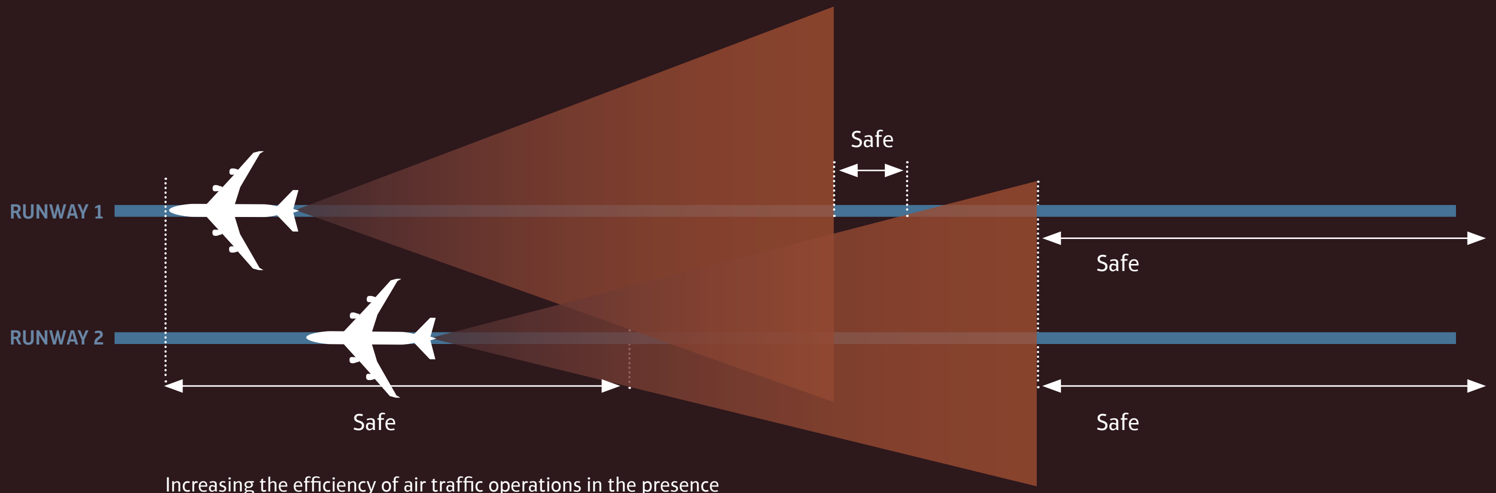
Our department includes experts in air transportation technologies, air traffic control, and aviation safety who serve on numerous government advisory committees. The department houses the International Center for Air Transportation, with the mission of discovery and dissemination of the knowledge and tools underlying a global air transportation industry. We lead the Global Airline Industry Program, a multidisciplinary team of faculty, staff and graduate students drawn from the MIT Schools of Engineering, Management, and Humanities and Social Sciences, along with colleagues at other colleges and universities, who collaborate to advance the economics, management, and operations of air carriers. The scope includes interactions with airline companies, aircraft and engine manufacturers, airports, air traffic control, and regulatory or supervisory agencies such as the U.S. Federal Aviation Administration and the International Civil Aviation Organization. The airline research team is advised by a board of 15 senior executives from the air transportation industry.

Department faculty and students have made pioneering contributions to the safety and efficiency of air transportation. Some of these include: system design and human factors studies for the Terrain Awareness and Warning System (TAWS), which is now mandatory on all U.S. and most international air carrier aircraft; contributing to improved flight safety through research on aviation weather hazards such as microbursts and aircraft icing; developing and testing low noise CDA approach procedures, which are being implemented worldwide; leading the application of queuing approaches to modeling and optimizing air traffic control systems; writing an authoritative text on airport planning; and developing airline revenue management system algorithms that are now common in the industry. Through programs such as the Silent Aircraft Initiative and PARTNER, we are pioneering the integration of environmental impact considerations in air transportation.

To address the major issues requires collaboration among researchers in systems engineering, navigation, dynamics and control, human supervisory control, environmental impact modeling, economics, operations research, and technology and policy.

U.S. FLIGHT DELAYS





Increasing the efficiency of air traffic operations in the presence of uncertainty while ensuring safety is one of the challenges being addressed by Professor Hamsa Balakrishnan.

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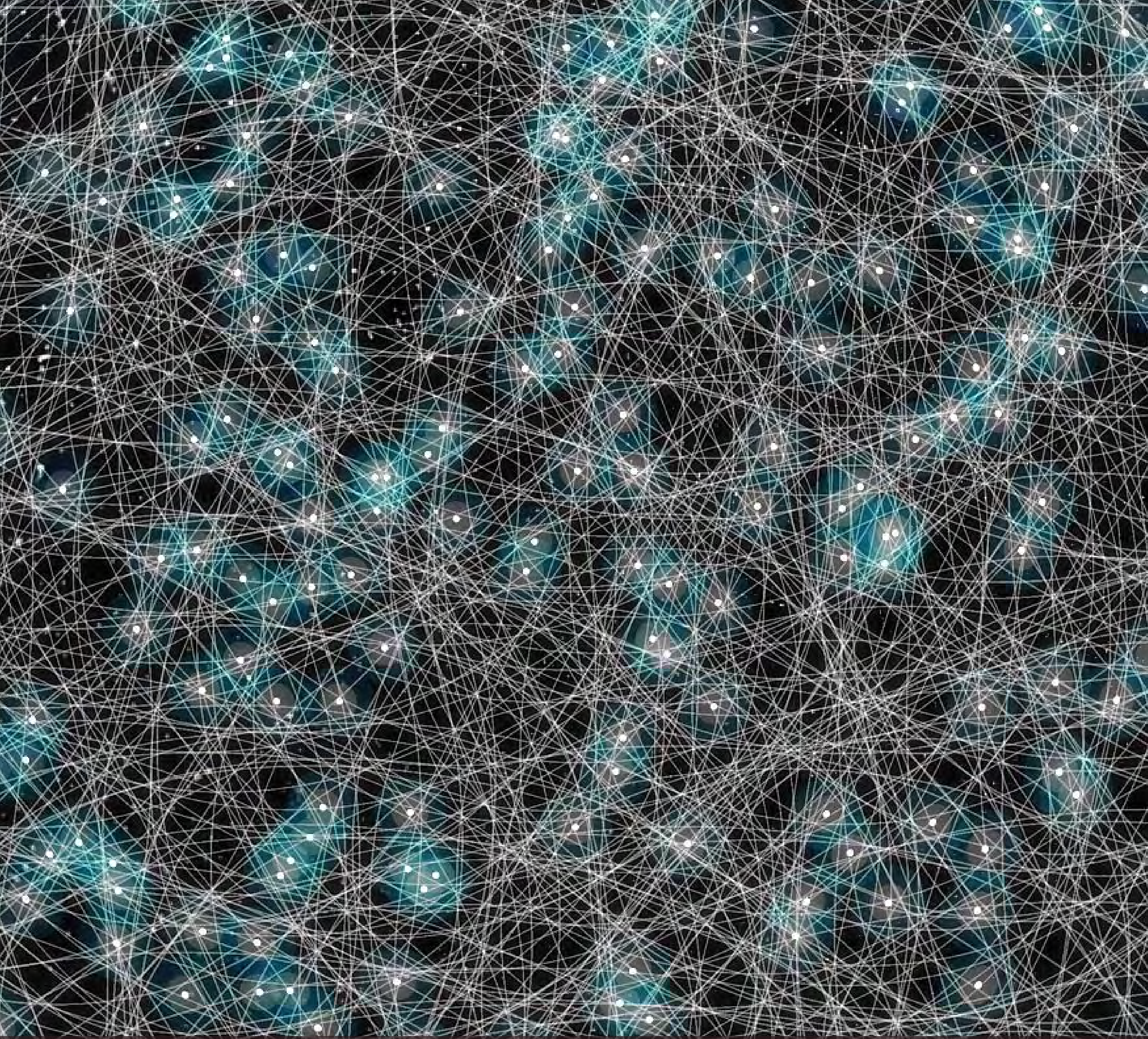


Animation still of Low Earth-Orbiting Satellites generated using 2005 Satellite Situation Report data.

(D. SCOTT HESSELS AND GABRIEL DUNNE, "CELESTIAL MECHANICS" HTTP://CMLAB.COM)

FIELDING OF LARGE-SCALE COMPLEX SYSTEMS

The aerospace industry designs, implements, and operates systems that are so complex that it is not possible for any one person to completely understand the entire system. One example is the Joint Strike Fighter, which is being developed by a geographically distributed team consisting of 8000 design engineers, half of whom are computer scientists. Another example is the NASA Constellation project, which will create a replacement for the Shuttle and conduct manned missions to the Moon and to Mars, and which is anticipated to take decades to design, implement and operate. Yet another is the new Missile Defense System, which involves integrating hundreds of separate systems, some of which have existed for decades (e.g., early warning systems) with new radar and delivery systems.

New systems may contain millions of lines of software, tens of thousands of physical components, and hundreds of subsystems of various types and technologies. Further, while flight control software failures can be just as disastrous as a broken wing spar, very different methods are required to design, evaluate, and ensure the safety of these integrated systems. In addition, it is now recognized that the technological parts of these systems cannot be divorced from the social and organizational parts; the systems must be developed and modeled as socio-technical systems, not simply technical systems.

> **Many aerospace systems are so complex that it is not possible for any one person to completely understand them.**

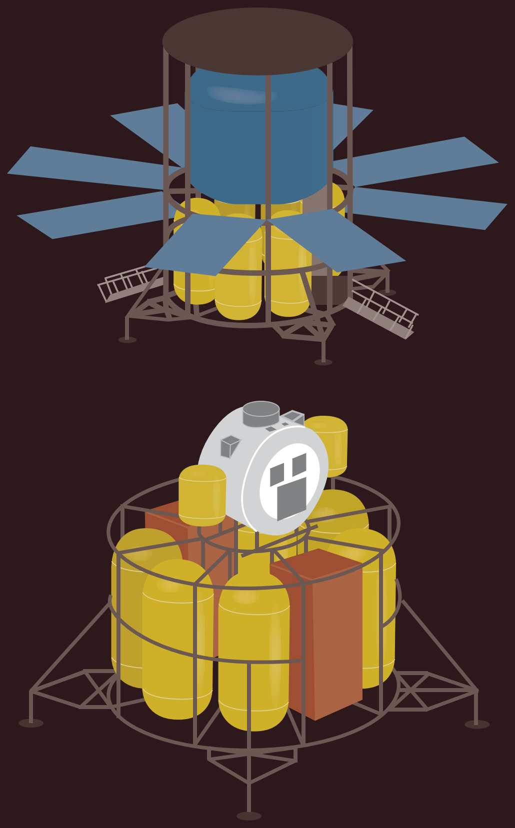
Traditional systems engineering processes, where functional requirements are contractually agreed to and frozen early, are not effective for the expensive, complex, and long-lifecycle systems described above. Because development cycles typically can take 5-10 years or longer, external factors and needs change over time, and systems are sometimes obsolete by the time they are fielded. An example is the commercial communications satellite constellations of the mid-1990s (e.g., Iridium, Globalstar) whose usage predictions were confounded by the rapid emergence of competing terrestrial wireless systems. This led to cumulative losses exceeding $5 billion and the collapse of the commercial satellite and launch industries in the late 1990s. The challenge is to develop strategic approaches to the fielding of large systems such that they can more easily evolve over time, adapting to shifting user and operator needs, emerging technologies, changing policies, and regulations. The opportunity is to maximize lifecycle value by including considerations of modularity, flexibility, commonality, and staged deployment.

07

The issues mentioned are not unique to aerospace systems, but aerospace is facing many of these problems before other industries. Our department is developing new approaches to modeling and analysis; ensuring system properties such as safety, security, reliability, flexibility, sustainability, and operability. We are also developing general risk and opportunity management techniques to understand the relationships and tradeoffs among these system properties; managing complex engineering projects; and addressing the design of systems composed of hardware, software, and humans that interact to achieve common goals.

Our department is closely involved with the new NASA manned space program to return to the Moon and send astronauts to Mars. MIT faculty and graduate students are helping to design system and software architecture. They have developed a new risk management approach to assist with program management decision making, designed tools for planning the program's logistics, and created an innovative safety engineering approach for the Space Shuttle replacement vehicle. In addition, new safety analysis tools have been used in the new U.S. Missile Defense System to evaluate the potential for inadvertent launch, resulting in identification of extra protection and changes required before the system could be deployed and tested. The Missile Defense Agency has adopted these tools as its primary approach to safety.

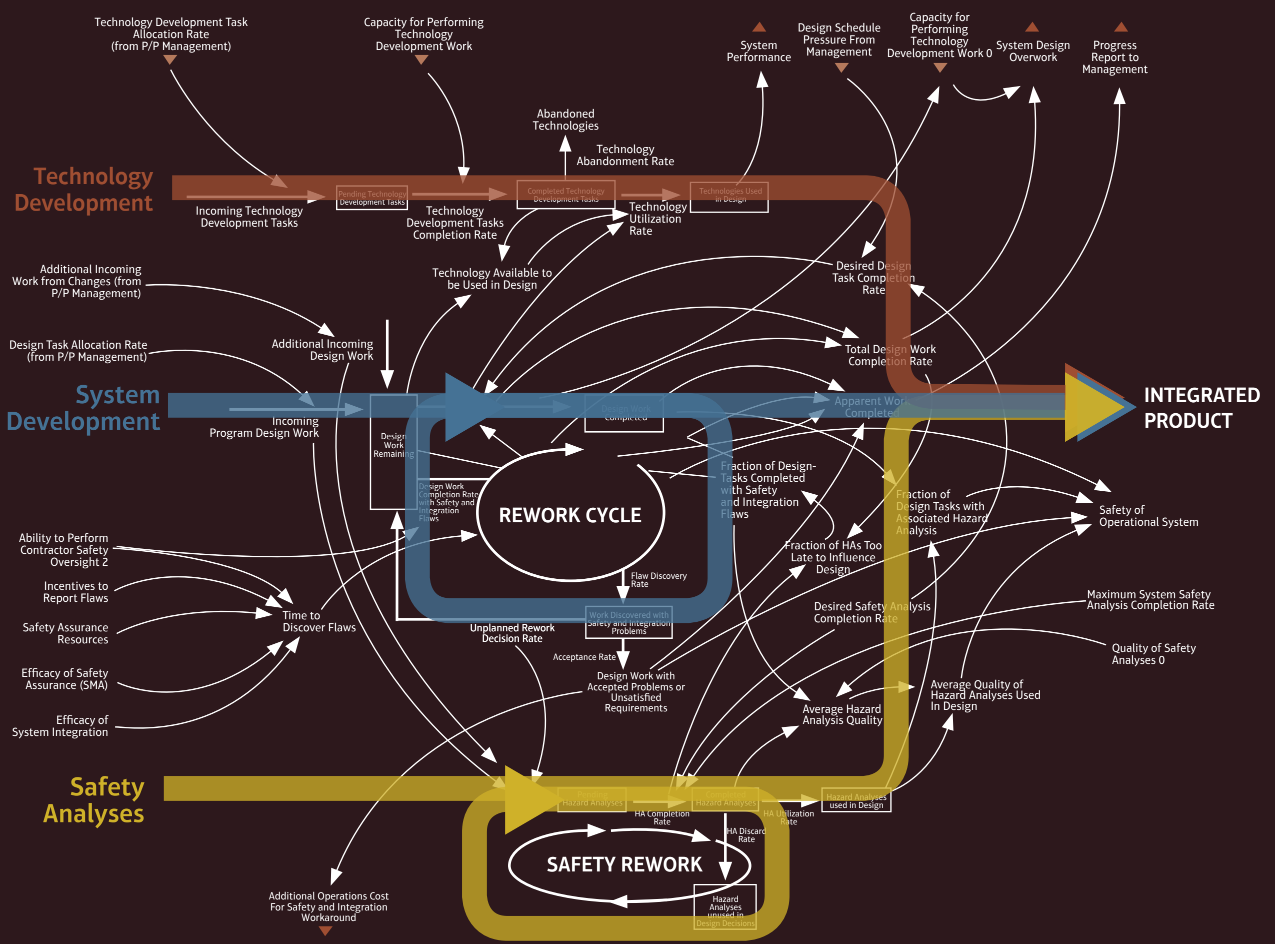
Our abilities to address these complex socio-technical systems are augmented by cross-disciplinary bridges to other departments in MIT's School of Engineering and Sloan School of Management.



Concepts for a pre-deployed lunar outpost (top) and a lunar lander developed for NASA by Aero-Astro students and faculty working with Professor Edward Crawley.

Boeing 737s travel along a new moving production line. The line enhances quality and reduces flow time and inventory levels when creating complex systems. (BOEING)

ENGINEERING - SYSTEM DEVELOPMENT COMPLETION AND SAFETY ANALYSES



A section of a systems dynamics model depicting NASA's Exploration Systems Mission Division development process. The model, constructed by Professor Nancy Leveson's Aero-Astro Complex Systems Research Lab students, will help manage risk in human spaceflight.

In the spring of 2007 the MIT Aero-Astro team, including students Carl Engel (left) and Adam Woodworth, bested others from throughout the United States to take first place in the American Institute for Aeronautics and Astronautics' prestigious Design/Build/Fly competition. (KEVIN KOLLER, RAYTHEON MISSILE SYSTEMS/AIAA)

> **"A stunning achievement … as an airplane designer guy, I feel a bit humble."**
>
> BOB LIEBECK, *BOEING SENIOR TECHNICAL FELLOW AND MIT AERO-ASTRO PROFESSOR OF THE PRACTICE*

08

ADVANCING ENGINEERING EDUCATION

On April 22, 2007, eight MIT Aero-Astro students accomplished something that has never been done. They designed a 1.9 pound airplane that flew a 3.5 pound payload on a prescribed course, winning the AIAA Design-Build-Fly competition, bettering their nearest challenger by a factor of 2.5 in points. The fact that they did something that has never been done is not the real story — our undergraduates frequently do such things — the real story is how they did it.

In 2006, many of the same students worked with Aero-Astro faculty members as part of a year-long MIT class focused on the AIAA competition. They conceived new designs which they analyzed, built, and tested. Three teams entered the competition, with the top team finishing in 11th place — an outcome we considered successful because it was the first time in many years that we had entered this very competitive event. However, the students were not satisfied. In 2007, they took matters into their own hands — working independently outside of class to design a vehicle and enter the contest. They showed us that the spark of ingenuity, the thirst for leadership, and the capabilities for world-class engineering excellence run deepest in our students.

> **The spark of ingenuity, the thirst for leadership, and the capabilities for world-class engineering excellence run deepest in our students.**

Sometimes we just need to get out of their way.

One can argue as to whether the faculty added drag or propulsion to the fine efforts of the students described above. We think it is more of the latter, and we are proud that the students credit their win in large part to applying the systems engineering principles they learned in our department. In the last 10 years, we have put a major focus not only on efforts to provide a learning environment that promotes ingenuity, leadership, and the development of world-class engineering and research capabilities, but also on assessing ourselves on how well we are doing this. We started by listening to our stakeholders: students, industry, government, and academia. We learned that modern engineers must be knowledgeable in all phases of the aerospace system life cycle: conceiving, designing, implementing, and operating. We adopted this as the context for a new form of undergraduate engineering education — CDIO — as a means to motivate our students to master a deeper working knowledge of the technical fundamentals while at the same time giving them the skills, knowledge, and attitudes necessary to lead in the creation and operation of new products, processes, and systems. As components of the approach, we reformed the way we teach, redesigned our curriculum, and raised $23 million for a state-of-the-art renovation of our teaching laboratories. Other universities are now contributing to achieving this vision, and today the MIT-led CDIO Initiative has been adopted at 27 engineering schools in China, Europe, Africa, the Middle East, as well as the United States (see http://www.cdio.org).

This was a successful outcome. However, as with the initial 11th place finish in the Design-Build-Fly competition described above, it also highlighted more that could be done. Last year we turned our attention to our graduate educational program. It has existed in the same form for decades, and we do not have data to assess whether the program is achieving the desired results or not. This does not mean the system is broken — we graduate some of the most talented graduate students in the world — but we want to do better, and to define why and how we are doing better. Thus, the department has stepped up to rethinking our graduate education programs. We wish to retain the unique, valued-added components that have been the hallmark of our historical excellence, but also to improve to a new level. Will the resulting reforms be as significant as those that dramatically altered our undergraduate programs? It is too soon to tell. But, last year a team of 15 faculty and graduate students completed a detailed review of our graduate program, leading to a series of recommendations for improvement in graduate admission processes, curriculum, mentoring, and assessment. With strong faculty and graduate student support, we are now working to design and implement changes. Five years from now, we expect that our graduate degree programs will look very different than they do today. We look forward to sharing these changes.

In the meantime, we take a cue from the above example: when appropriate we will stand aside, and let the truly great young minds and hands of our students lead the way.

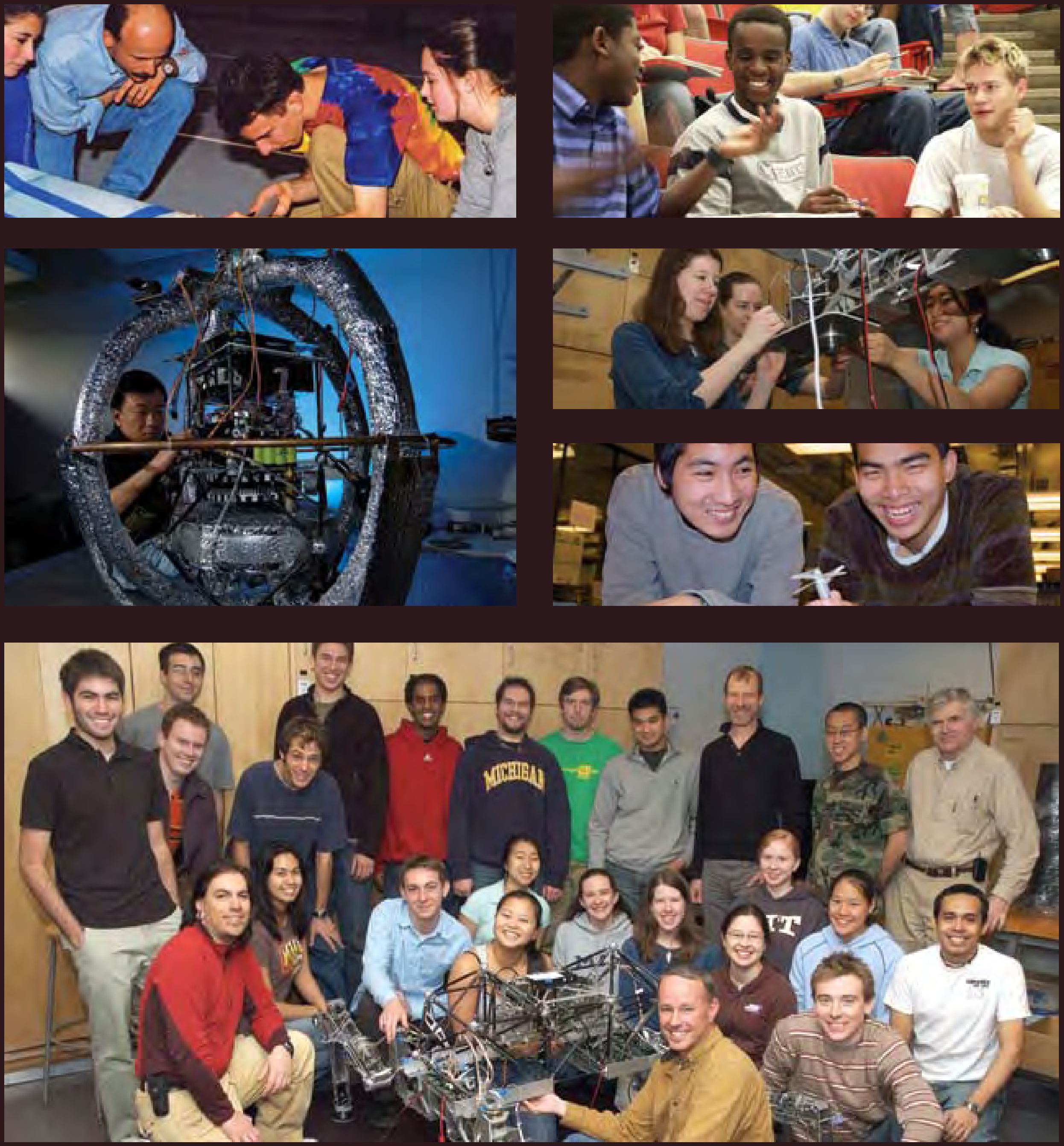
AIAA

The Aero-Astro winning 2007 AIAA Design/Build/Fly team: (back, from left) Brandon Suarez, David Sanchez, George Kiwada, Adam Woodworth; (front, from left) Nii Armar, Ryan Castonia, Carl Engel, Fuzhou Hu.

MENS ET MANUS

Modern engineers must be knowledgeable in all phases of the aerospace system life cycle: conceiving, designing, implementing, and operating.

In the Gerhard Neumann Hangar, part of Aero-Astro's Learning Laboratory, students can construct and test large objects, like this human-powered centrifuge designed to offer exercise and artificial gravity in zero-G. (WILLIAM LITANT)



MIT Aero-Astro education stresses engineering fundamentals, set in the context of the conceiving-designing-implementing-operating process. It is rich with student projects complemented by internships in industry. It features active, exciting, and fun group learning experiences in both classrooms and in our modern learning workshop/laboratory. Our students make advances in aerospace engineering through formal coursework, extracurricular activities, and graduate and undergraduate research.

08

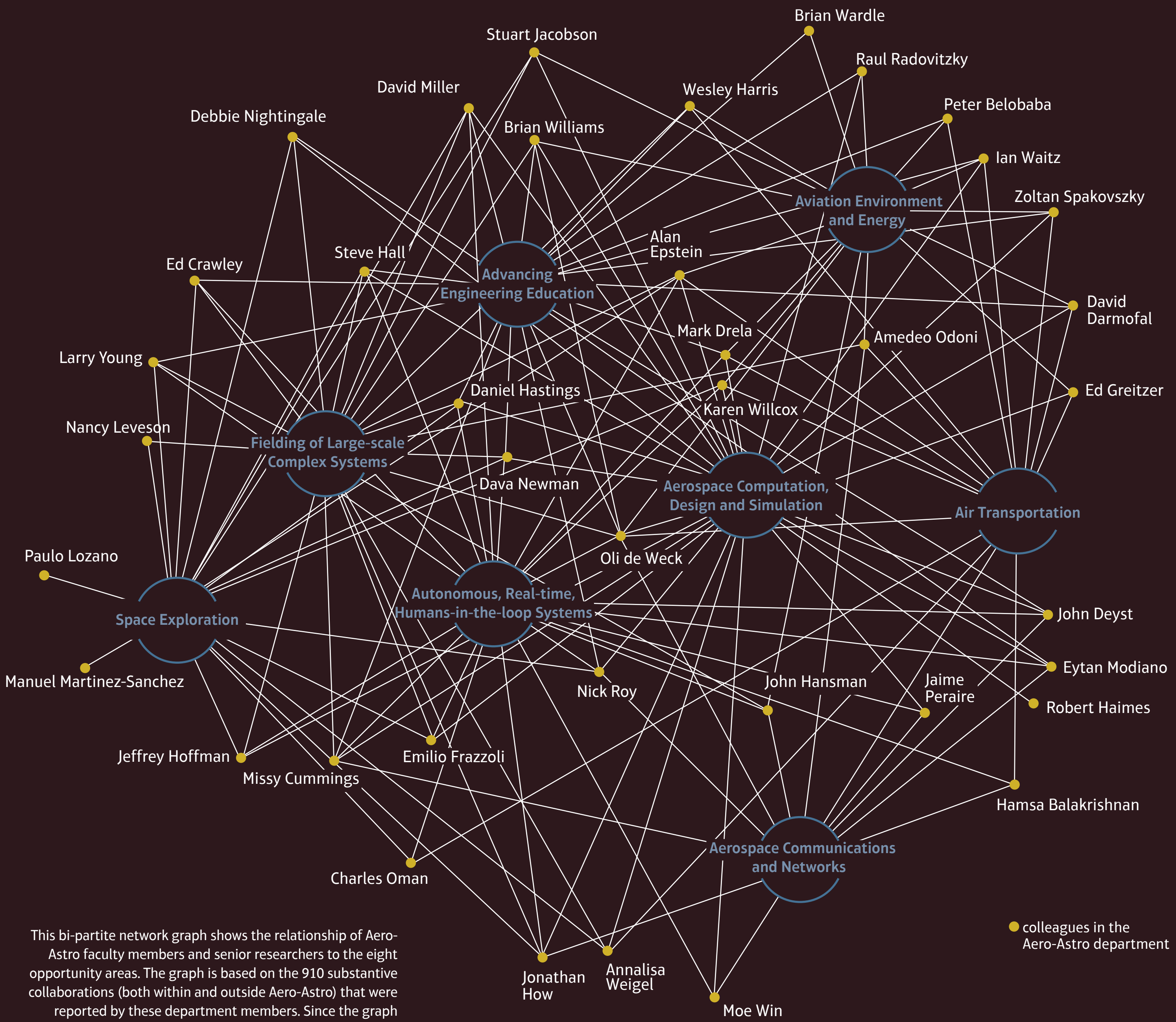
WE ARE CONNECTED

The students, faculty, and staff of the MIT Department of Aeronautics and Astronautics work with each other, with colleagues across MIT, and with colleagues from institutions throughout the world. Our linkages enable us to tackle challenging multidisciplinary problems. These linkages also amplify our contributions. As a result, our department is an exciting and rewarding place to work and learn. The environment is connected, busy, global, hectic, open, collegial, and fun.

One example of our collaborative approach to solving multidisciplinary problems is our leadership of the 50-person team that designed and tested shirt-button-sized gas turbine engines and electric generators made from silicon that spin at more than one million revolutions per minute. These devices have applications in micro-UAV propulsion and portable power. The team spanned the departments of Aeronautics and Astronautics, Electrical Engineering and Computer Science, Mechanical Engineering, and Chemical Engineering, and included participants from Georgia Tech, University of Maryland, and Clark-Atlanta University. The work led to the creation of a new field of power electro-mechanical systems, which has since spawned government and university programs, annual conferences, and hundreds of journal publications.

Our linkages enable us to tackle challenging multidisciplinary problems.

A second example is our leadership of the Lean Aerospace Initiative (LAI), a research and learning consortium comprising MIT faculty members from several engineering departments and the Sloan School of Management, 20 major aerospace companies (and their suppliers), and eight major government agencies including the Air Force, Navy, Army, Defense Contract Management Agency, and Defense Finance and Accounting Service. By serving as a neutral forum for learning to more effectively, efficiently, and reliably create value, LAI is a catalyst for the organizational transformation that is unfolding throughout



This bi-partite network graph shows the relationship of Aero-Astro faculty members and senior researchers to the eight opportunity areas. The graph is based on the 910 substantive collaborations (both within and outside Aero-Astro) that were reported by these department members. Since the graph is based only on reported collaborations, it does not reflect some individual activities in these areas — for example, faculty members working with graduate students where there are not significant external collaborations. This graph, and those on the following pages, were developed by Gergana Bounova, Oli de Weck, and Ian Waitz.

the U.S. aerospace industry. LAI's work has sparked similar efforts in a variety of partners, including Boeing, Raytheon, Lockheed Martin Space Systems and the U.S. Army. Results have included improvement by a factor of four in program cycle time and throughput, and 60 percent improvement in engineering hours, resulting in shorter development times at reduced costs. Two aircraft programs saved $110 million and $80 million, respectively, employing LAI lean practices. Five more programs saved more than $100 million in development and contracting costs, and $26 million in test equipment.

The enabling effects of collaboration are evident in each of the eight opportunity areas.

In addition to a culture of collaboration, we also have a culture of measuring our performance to better understand how effective we are, and more importantly, to understand how we may improve. These continuous improvement activities range from formal research in educational assessment, to the reflective memos required of all faculty members who teach undergraduate classes, to being the first department at MIT to design and implement online subject evaluations, to a newly implemented requirement for written semester progress reviews for all graduate students, to measuring how much time our sophomores spend on every assignment in Unified Engineering so that we can maintain balance between what many describe as the most challenging subject sequence at MIT and our students' other important educational and personal endeavors.

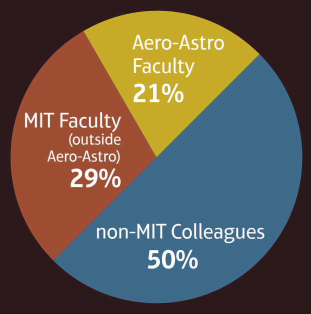
We strive to be an organization that learns.

Therefore, when we sought to understand our current capabilities in the eight opportunity areas, and to assess the strength of our collaborative culture, we collected data. Forty faculty members and senior research engineers responded. They reported more than 900 substantive collaborations that have occurred in the last four years. Here, collaboration is defined as working together to solve a research problem or to produce an educational advance. To be considered substantive, the activity had to be more than simply sharing a funding source, or writing a proposal with a colleague, or co-teaching an existing course. However, it could be something different than working together on a funded research project—for example, jointly authoring a paper when no joint funding is involved, or jointly developing a new course.

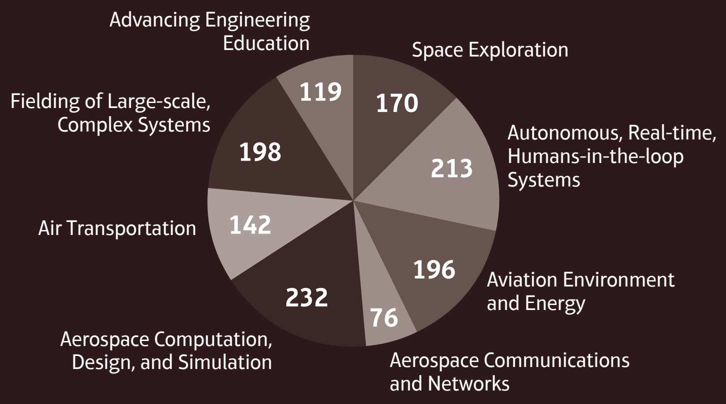
The linkages shown provide us with unique capabilities: the whole is greater than the sum of the individual parts.

This type of collaboration is inherent in the world of aerospace, where systems are designed and developed on a multi-organizational and multinational basis. Through these collaborative processes we are simultaneously enhancing the ability of the overall enterprise to solve problems, and introducing our students to the development of teaming skills critical to their future.

MORE THAN 900 UNIQUE COLLABORATIONS

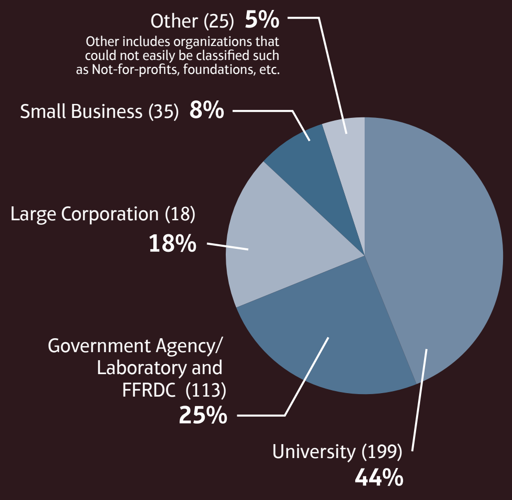


COLLABORATIONS REPORTED BY OPPORTUNITY AREA

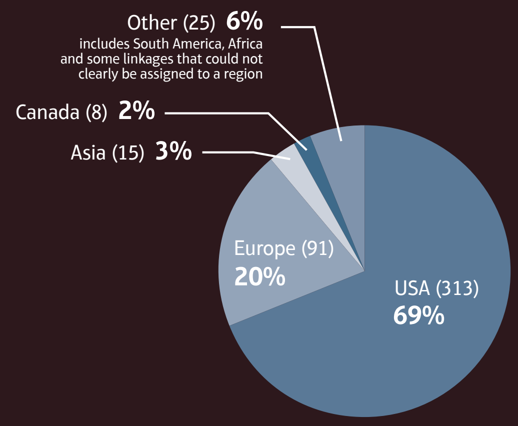


The breadth of our contributions in these areas is evidenced by the 117 different journals in which our faculty members published in the last four years.

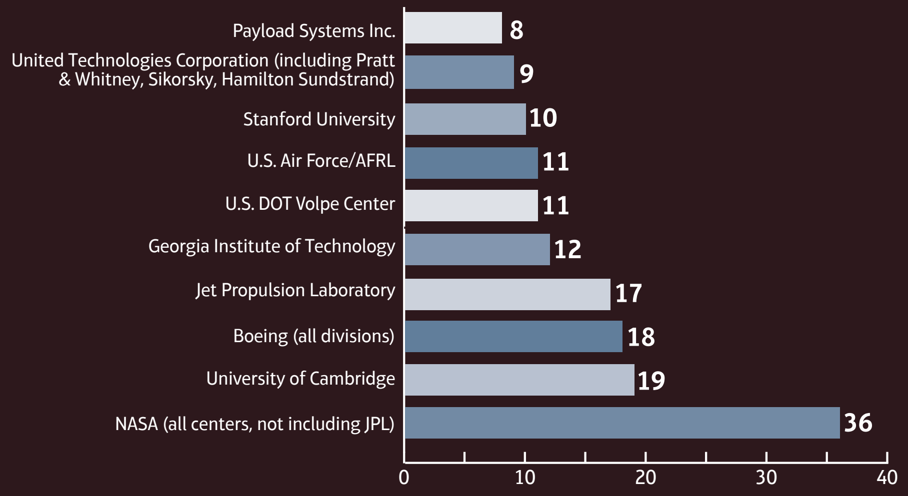
NON-MIT COLLEAGUES BY TYPE OF INSTITUTION



NON-MIT COLLEAGUES BY REGION

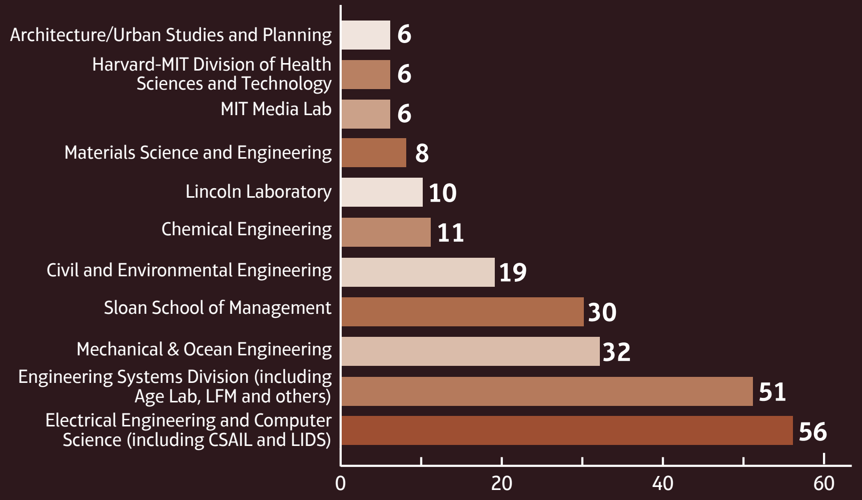


HALF OF OUR COLLABORATIONS ARE WITH NON-MIT COLLEAGUES (452 TOTAL)



External organizations for which 4-7 collaborations were reported: Arizona State University (4), Bell Labs (4), DARPA (4), Draper Laboratory (4), FAA (6), Harvard University (incl. Harvard Medical School) (5), Lockheed Martin (6), MVA Consultancy (4), Northrop Grumman (6), Rolls-Royce (4), Rutgers University (4), Singapore Universities (6), University of Bologna (6), University of California Berkeley (6), University of California Santa Barbara (4), University of Maryland (6).

ONE QUARTER OF OUR COLLABORATIONS ARE WITH MIT COLLEAGUES WHO ARE NOT IN AERO-ASTRO (262 TOTAL)



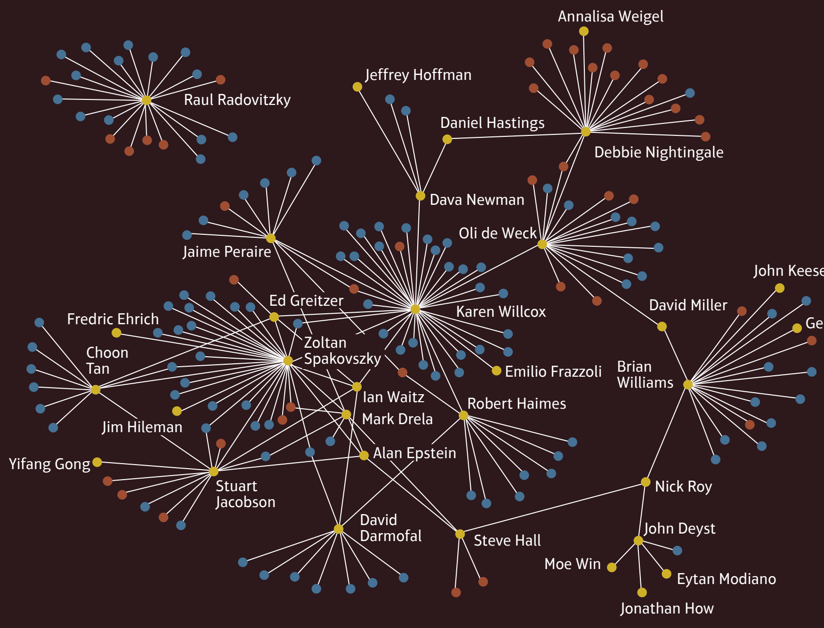
MIT groups for which 5 or fewer collaborations were reported: Mathematics (5); Earth Atmospheric and Planetary Sciences (4); Nuclear Engineering (3); Science, Technology and Society (3); Microsystems Technology Laboratory (2); MIT Kavli Institute for Astrophysics and Space Research (2); Brain & Cognitive Science (1); Biology (1); Cambridge-MIT Institute (1), Laboratory for Energy and the Environment (1); MIT Ford Program (1); Political Science (1); Office of Undergraduate Education (1); and Media Arts and Sciences (1).

COLLABORATIONS MULTIPLY OUR CAPABILITIES

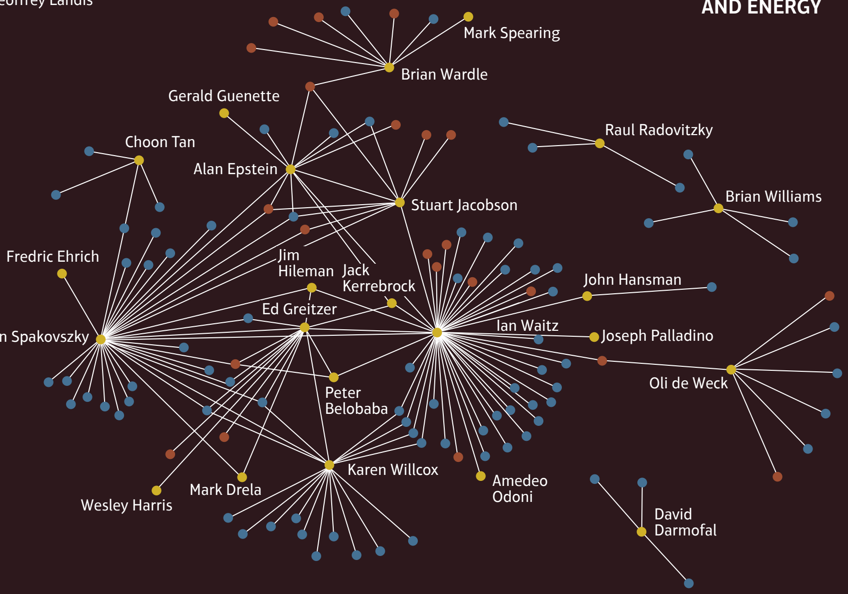
On these pages we show network graphs of our collaborations during the last four years mapped to the eight opportunity areas. (We are engineers after all.) The 910 collaborations reported include 146 different MIT colleagues who are not in the Aero-Astro department (red points), and 361 colleagues from outside MIT (blue points). One quarter of the collaborations were within our department, one quarter with others at MIT, and half with people outside MIT — ranging from people in other parts of Cambridge, Massachusetts to people in Seattle, South Africa and Singapore. The connections are substantive and frequent: 34 percent occurred weekly or more frequently, and 39 percent between weekly and monthly.

● colleagues in the Aero-Astro department
● MIT colleagues who are not in Aero-Astro
● colleagues from outside MIT (319)

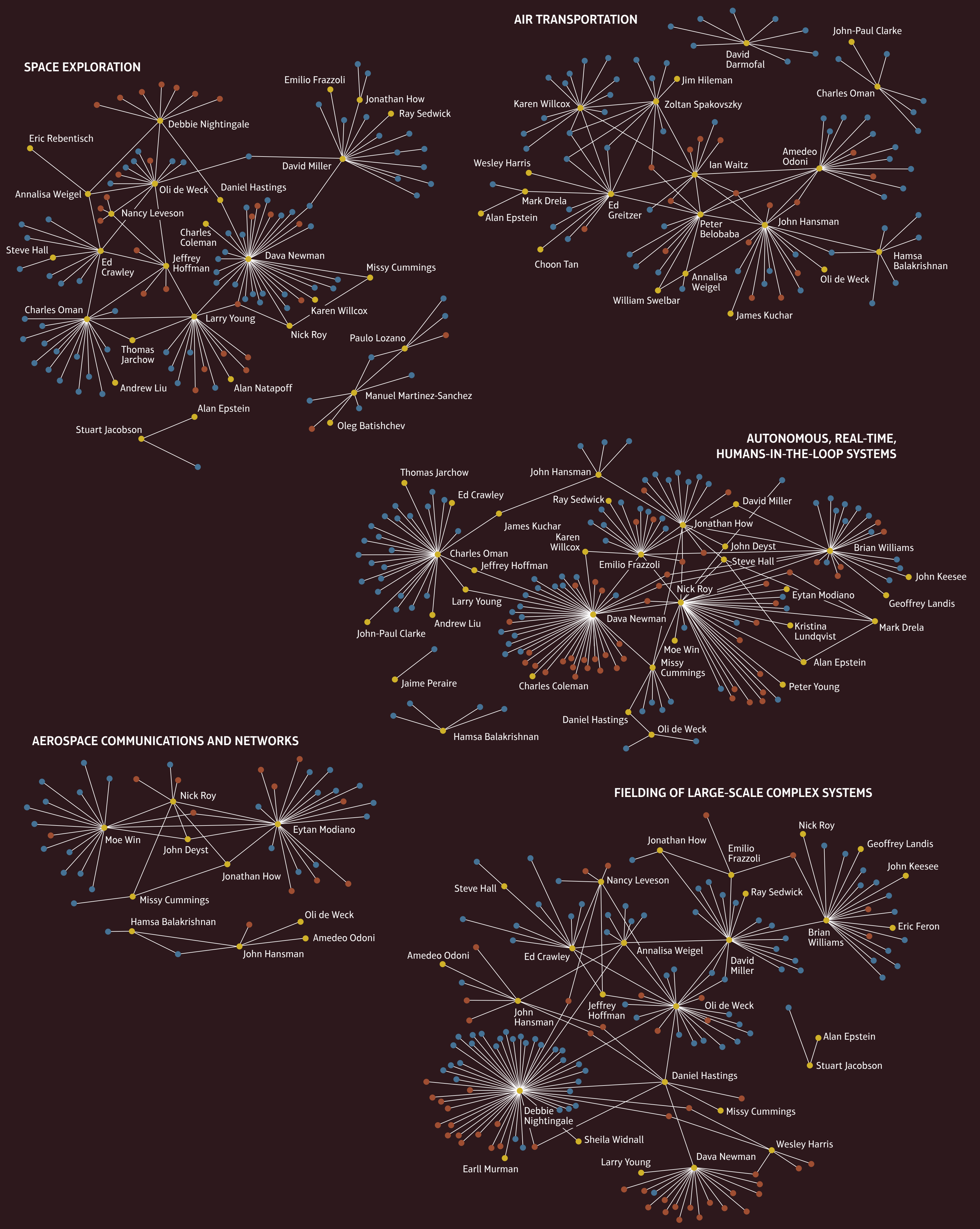
AEROSPACE COMPUTATION, DESIGN AND SIMULATION



AVIATION ENVIRONMENT AND ENERGY



ADVANCING ENGINEERING EDUCATION

SPACE EXPLORATION
Debbie Nightingale
Eric Rebentisch
Emilio Frazzoli
Jonathan How
Ray Sedwick
David Miller
Annalisa Weigel
Oli de Weck
Daniel Hastings
Nancy Leveson
Charles Coleman
Steve Hall
Ed Crawley
Jeffrey Hoffman
Dava Newman
Missy Cummings
Charles Oman
Larry Young
Karen Willcox
Nick Roy
Paulo Lozano
Thomas Jarchow
Andrew Liu
Alan Natapoff
Manuel Martinez-Sanchez
Alan Epstein
Oleg Batishchev
Stuart Jacobson
AIR TRANSPORTATION
David Darmofal
John-Paul Clarke
Jim Hileman
Karen Willcox
Zoltan Spakovszky
Charles Oman
Amedeo Odoni
Wesley Harris
Ian Waitz
Mark Drela
Ed Greitzer
Alan Epstein
Peter Belobaba
John Hansman
Choon Tan
Hamsa Balakrishnan
Annalisa Weigel
Oli de Weck
William Swelbar
James Kuchar
AUTONOMOUS, REAL-TIME, HUMANS-IN-THE-LOOP SYSTEMS
Thomas Jarchow
John Hansman
Ed Crawley
Ray Sedwick
David Miller
Jonathan How
James Kuchar
Karen Willcox
John Deyst
Charles Oman
Jeffrey Hoffman
Emilio Frazzoli
Steve Hall
Brian Williams
John Keesee
Nick Roy
Eytan Modiano
Geoffrey Landis
Larry Young
Dava Newman
Andrew Liu
John-Paul Clarke
Kristina Lundqvist
Mark Drela
Moe Win
Missy Cummings
Alan Epstein
Jaime Peraire
Charles Coleman
Peter Young
Daniel Hastings
Oli de Weck
Hamsa Balakrishnan
AEROSPACE COMMUNICATIONS AND NETWORKS
Nick Roy
Moe Win
John Deyst
Eytan Modiano
Jonathan How
Missy Cummings
Oli de Weck
Hamsa Balakrishnan
Amedeo Odoni
John Hansman
FIELDING OF LARGE-SCALE COMPLEX SYSTEMS
Nick Roy
Geoffrey Landis
Jonathan How
Emilio Frazzoli
John Keesee
Nancy Leveson
Ray Sedwick
Steve Hall
Eric Feron
Brian Williams
Amedeo Odoni
Ed Crawley
Annalisa Weigel
David Miller
John Hansman
Jeffrey Hoffman
Oli de Weck
Alan Epstein
Stuart Jacobson
Daniel Hastings
Debbie Nightingale
Missy Cummings
Sheila Widnall
Wesley Harris
Earll Murman
Larry Young
Dava Newman

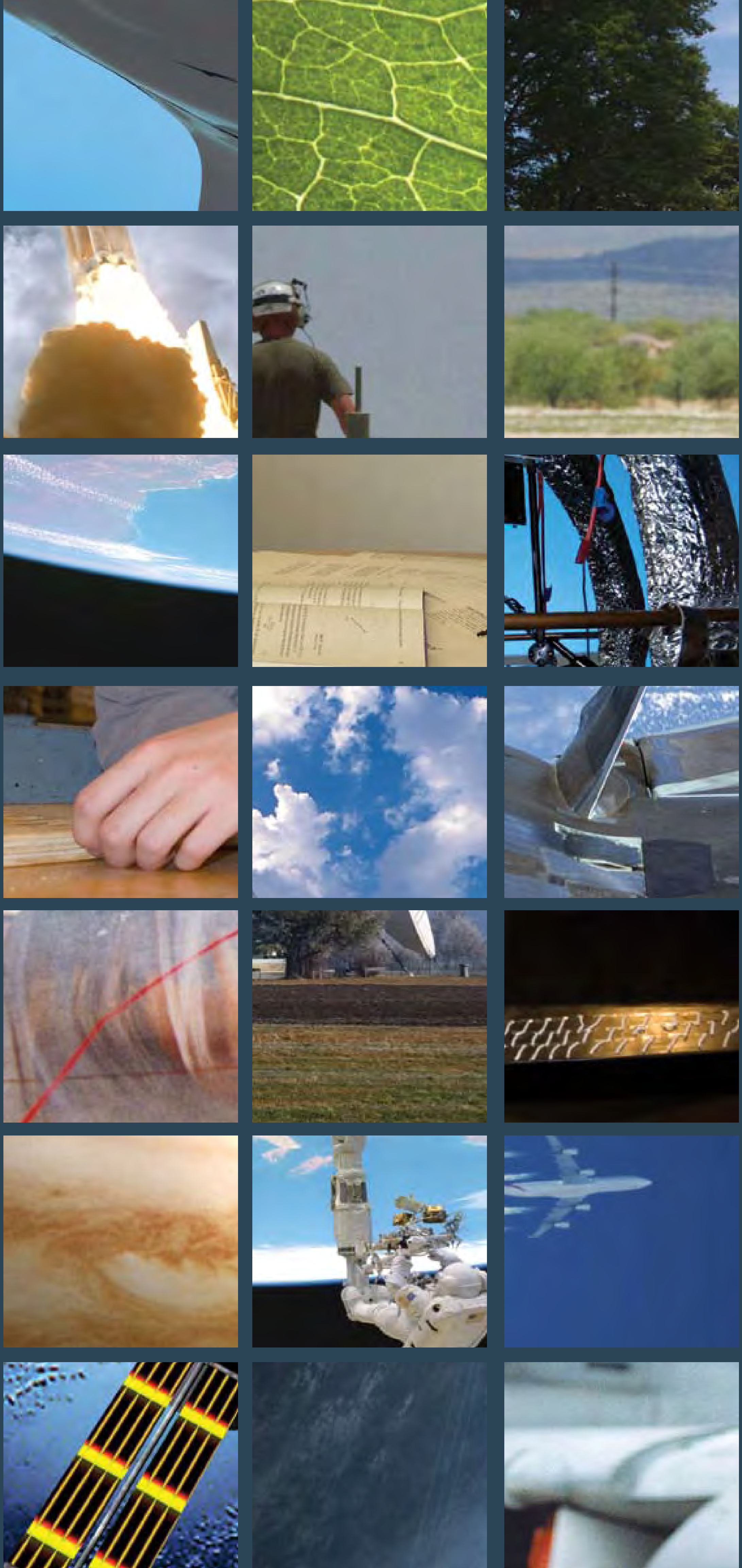
SUMMARY

WHAT DOES OUR FUTURE HOLD?

We do not know what the future will hold. However, from our current vantage point, we are enthusiastic about our department and the field of aerospace.

Our department has a tradition of both strong scholarship, and of contributing to the solution of “industrial-strength” problems. Our reach within aerospace extends to high levels of policy and practice. Our community includes a former space shuttle astronaut, a former secretary of the Air Force, two former NASA associate administrators, three former Air Force chief scientists, 12 members of the National Academy of Engineering, and 16 Fellows of the American Institute of Aeronautics and Astronautics. Department members have been executives in the aerospace industry and founders of companies.

While our history is a legacy we treasure, this document has focused on two much more important questions: What is the current state of our department, and what do we plan for the future?



OUR CURRENT STATE

We are a vibrant, connected department, recently invigorated with 26 faculty hires, and focused on three areas: aerospace vehicle engineering, the engineering of large-scale, complex aerospace systems, and aerospace information engineering. We are advancing the state-of-the-art in air transportation, exploration, communication, and national security.

OUR PLAN FOR THE FUTURE

We have defined eight areas that represent grand challenges and grand opportunities. We will build our capabilities to contribute further to these areas. We will do this by striving for excellence in the core disciplines that underlie these areas, but also by continuing to emphasize and promote the collaborative problem solving that is required for tackling the complex, multidisciplinary problems that characterize our industry. By doing so, we will be well positioned to pursue the opportunities of today, and the new opportunities that will arise in our future.

Please visit us at MIT to learn more.

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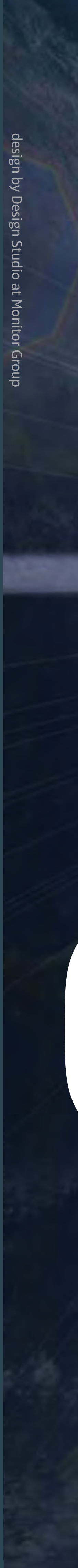

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