Left to right: Joel Burdick, Soon-Jo Chung, Yisong Yue, Anima Anandkumar, Aaron Ames, and Mory Gharib

Smart from the Start

Studying and Building Autonomous Systems

Drivers, pilots, and households are routinely able to set increasingly sophisticated systems on autopilot, thanks largely to the layering of multiple breakthroughs in separate domains like voice recognition, image classification, and sensors. The conversation about how to carry autonomous technology forward across disciplines and applications has had a natural place in the Division of Engineering and Applied Science. The question has been how to best approach autonomy from the start. The answer has meant identifying autonomous systems as a research priority for the EAS Division, creating a space for autonomy to come into its own and resisting the trend to treat it as an add-on to any other engineering discipline. Instead, EAS has managed to create a nexus between the departments of aerospace (GALCIT), mechanical and civil engineering, electrical engineering, and computing and mathematical sciences.

When considering the next generation of these technologies, Mory Gharib, Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering and Director of Aerospace and the Center for Autonomous Systems and Technologies (CAST), defines the emerging autonomy as post-navigator: "These are systems that do not require an operator, or any third party, to make decisions to successfully navigate and safely achieve their goal while negotiating dynamic conditions," he explains. Housed within GALCIT, CAST operates as an interdisciplinary center dedicated to the study of this new frontier: the emerging unknowns of the engineering of autonomous systems. The new center brings together researchers from EAS, JPL, and Caltech's Division of Geological and Planetary Sciences in a state-of-the-art, 10,000-square-foot facility where they can work alongside experimental machines—build and test robots and drones, for example—to advance bioinspired systems, autonomous exploration, and other related fields with a range of important potential applications.

Establishing a research program surrounding systems that do not yet exist requires a collaborative environment, with room for large teams to conduct research along with sophisticated testing facilities and a highly integrated educational model. "EAS has always pushed the boundaries of breakthrough research while educating the leaders of the future. The result is a culture that attacks the unknown with fundamental science," says G. Ravichandran, John E. Goode Jr. Professor of Aerospace and Mechanical Engineering and the Otis Booth Leadership Chair of the EAS Division. "By clearing a space and building a dedicated specialized home for autonomy, the aerospace department grows beyond itself, making way for more universal

Robot explorers working together to navigate unknown and complex terrestrial environments

applications of the systems it has influenced for decades.” Gharib concurs. “Engineers and applied scientists from across Caltech and JPL now have a venue for collaboration that will have real and significant impact outside our immediate academic world,” he says. “This research will undoubtedly affect science, culture, and society. Making sure research of this magnitude has a dedicated space is an important expression of the EAS Division’s commitment to the exploding field of autonomous systems.” This commitment also extends to Caltech trustees Lynn Booth and Kent Kresa, who recently endowed the Booth-Kresa Leadership Chair for CAST.

ENGenious brought together some of the key faculty collaborators of CAST to hear how they use this new space and its specialized testing facilities and how the evolving structure of that research is redefining what engineering education means at Caltech.

Research on autonomy within EAS is mission-driven and oriented around shared “moonshot” projects. Each of the moonshots—mapped out thematically as Explorers, Guardians, Transformers, Transporters, and Partners—is an ambitious, innovative, and interdisciplinary endeavor designed to capture broad tracts of fundamental research throughout its development. Like their namesake—the challenge of sending Americans to the moon in the 1960s—CAST’s moonshot goals will require advances in engineering to accomplish currently impossible feats. Among these is the development of a robot that can walk from Mexico to Canada without assistance, other than being guided by a network of flying drone scouts; another project is the construction of a flying ambulance capable of delivering an injured person to first responders without a pilot.

The moonshots are fundamentally about helping: placing humans and machines on a team together to better navigate, monitor, survey, communicate, deliver, and assist in all manner of dynamic conditions. Under this model, the various engineering disciplines function democratically, with no one academic niche taking precedence. According to Gharib, this is the way to move past the traditional camps of hardware and software and set up systems more like the human body does. “It is a mind-body vision,” he explains. “We are all critical, and each moonshot mandates the participation of multiple experts. The point of interface between the minds and the bodies of these systems is where the engineering will break out of one department and radiate throughout the Division and into our world.” This potential for greater world impact is also recognized by the corporate and industry supporters of CAST, including Raytheon and AeroVironment.

Some of the faculty involved focus on the bodies of the machines, drones, and robots that will directly impact human experience. Aaron Ames and Joel Burdick from the Department of Mechanical and Civil Engineering and Soon-Jo Chung in the Department of Aerospace work on guidance and control. Yisong Yue and Animashree (Anima) Anandkumar from the Department of Computing and Mathematical Sciences develop the “brains” that enable learning, decision-making, and intelligence, with platforms that can discern, digest, and close the information loop for the bodies they serve. The collaboration of these teams is essential to the progress of the research, particularly beyond the lab. Aaron Ames, Bren Professor of Mechanical and Civil Engineering and Control and Dynamical Systems, can take his robot bodies only so far without a mind: “To me, this step to autonomy means taking my robots out of the lab and into the wild. In order to do that, I cannot live in my silo, where the world is perfectly defined. I need expertise in dynamics and machine learning to make that happen. How else will my robots have the ability to handle unknown, unstructured events in a robust way?”

Joel Burdick, Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Bioengineering and JPL research scientist, recognizes that this kind of pioneering work brings challenge and opportunity alike, both of which necessitate collaboration. “It’s not like we can open up an engineering textbook and say to our students, ‘Go build an autonomous system.’ We have to build that together, from scratch,” he says. But it’s worth it, says Bren Professor of Computing and Mathematical Sciences Anima Anandkumar, who underscores the great potential of their efforts: “I see right here, right now, the opportunity to shape the fundamental framework of this field—one that will come to define the theory of autonomy.”

So how will they accomplish all this? If half the battle of successful engineering is asking the right questions—in this case, by way of the moonshot goals—then these teams have a great advantage in being able to frame those questions and seek the answers in the context of CAST and, more generally, the Caltech environment. According to Assistant Professor of Computing and Mathematical Sciences Yisong Yue, “There is consistent engineering serendipity at Caltech. You can count on it happening because we are small with strength in the fundamentals. Faculty and students interact and collaborate across the EAS Division and beyond organically. We all make the interesting and often unexpected connections that lead to the highest-impact research. CAST is a terrific example of this culture by design.” Understanding and maximizing this strength was a critical part of the vision of CAST, with an emphasis not

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> Autonomy really requires the mind and body coming together. We have to show intelligence and control. These are typically self-separate domains; at CAST it all comes together.
>
> Anima Anandkumar
> *Bren Professor of Computing and Mathematical Sciences*

just on collaboration but on the translation of ideas across academic disciplines—a very Caltech approach. "At Caltech, we all speak the language of mathematics, and that really makes the communication of different ideas much more efficient in terms of approaching a common problem from multiple angles," notes Yue. "This ability to jump in with a shared terminology, in combination with our small size, greatly reduces the friction that sometimes exists between disciplines at other schools. The result is an incubator culture for collaborative problem solving."

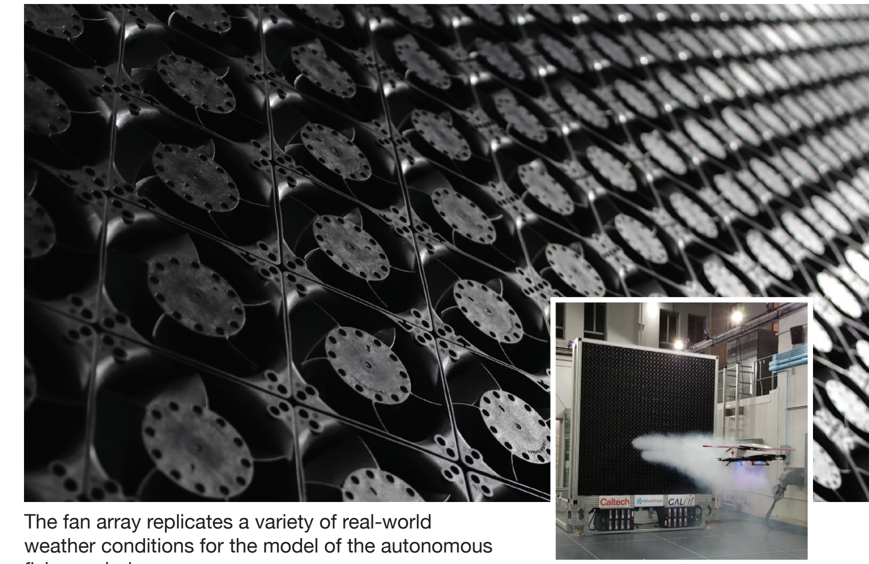
Answering big questions like those posed by the moonshots also requires careful planning and initial testing, which is the current stage of focus for the CAST researchers. "Now we are learning the math of the CAST moonshots," says Gharib. "We model heavily, and we ask ourselves, 'How do we design based upon the principles we see in the data?' We want to make sure from the beginning that no gadget is built before knowing it will be smart. It seems like a big question, but really, it requires great efficiency. You have to first have a good understanding of what is useful." The computing power required to achieve that level of understanding in the modeling and simulation phase is undeniably huge—an impressive learning problem, says Anandkumar, but one that can be approached systematically at CAST. "In many control problems, we already have algorithms designed by domain experts. However, these algorithms tend to be highly conservative," she explains. "Consider the example of landing a drone. That maneuver is slow and consumes a lot of battery power. We can learn better landing strategies in a data-driven way through two approaches: either by simulation or by the example of human experts. Human experts provide demonstrations of good landing, but we cannot rely uniquely on that modeling, as it takes too much time. On the other hand, the efficiency of simulators is convenient, providing lots of data quickly, with the added benefit of affording more mistakes that have no real safety implications. However, no matter how good the simulations are, there will always be a mismatch with the real world. Only when all of this real and simulated data is tested and refined do you gain the actual benefits. This is why a controlled testing environment like the drone lab here at CAST is so important."

This kind of learning requires a combination of high-level decision making and lower-level guidance and control. Their junction is the crux of CAST's initial testing. Associate Professor of Aerospace, Bren Scholar, and JPL Research Scientist Soon-Jo Chung says, "We teach our robots how to negotiate the unknown by creating the unknown using CAST's realistic simulation facilities, including the aerodrome and the space robotics lab. Aerial and space robots can better understand and negotiate uncertainty by predicting it in a way that encapsulates the top-level artificial intelligence *and* the low-level control." He adds: "The unique facilities here make that possible. We can set up unknown models, test the real-world conditions, collect data, collaborate, refine and improve our learning and control algorithms, then retest in-house. We can rapidly cycle through unknowns here because of these sophisticated facilities."

The state-of-the-art testing facilities amount to an important step forward in building that knowledge base. One key feature of CAST is its three-story enclosed aerodrome, an innovative reincarnation of the legendary wind tunnels of GALCIT's past. Chief project consultant David Kremers describes the flight arena as "the world's first real-weather wind tunnel, with the added benefit of being under a giant infrared microscope with a resolution of 100 microns, all in a space as unconfined as the Federal Aviation Administration will allow." The setup includes an elaborate fan wall—an array of 1,296 individually programmable fans—capable of creating a near-infinite variety of customizable wind dynamics, along with tiers of special cameras to capture all navigation and movement in the space as flying drones react. "There are universities building large spaces for flight," Kremers says, "but this fan wall and its capabilities are unique in the world for testing."

The Transporters moonshot endgame is the development of a fully autonomous flying ambulance. A flying machine capable of carrying a patient without any external information must be very stable and robust, able to compensate for everything from a mild breeze to the shears generated between skyscrapers. "The design and the developing autonomy of the flying ambulance are physics-driven," says Chung. "When we asked ourselves about the forces we had to negotiate and the degree of stability necessary, the question was: Rotors or wings? We decided the answer was both. We came to this platform design by incorporating aerodynamics, flight dynamics, and control theory. Actually testing our first model without the variety of conditions offered by the fan array would be extremely difficult if not impossible."

Another world-class physical feature of CAST is Chung's space robotics lab on the basement levels of the building. This near-frictionless environment allows his students to test physics-driven designs for spacecraft in three dimensions. This "flat floor"—the largest in academia, surpassed only by those held by NASA—is the kind of specialized facility that allows for advanced, efficient development and testing. Research currently underway in this lab, in partnership with JPL, will further the Transformers moonshot: A mini model asteroid, affectionately known



The fan array replicates a variety of real-world weather conditions for the model of the autonomous flying ambulance.

as "the potato," is serving as the visual unknown target for a swarm of space drones that are learning to characterize the size, weight, shape, and motion of foreign objects using onboard sensors. A swarm offers the advantage of exponential improvement in the precision and speed of the characterization of the target object.

For the Caltech students working in these facilities, who invest energy and passion in these first projects informing the moonshots, the goal is to be broad but targeted in their scientific approach, according to Ames. "We are framing autonomy for our students in a way that grounds them in an underlying golden thread of scientific discovery. Our job here is to take out all of the noise," he says. "The range of things students are going to have to know in order to study autonomy is immense. We are teaching what threads them together and optimizing the coursework so they receive just the right amount of information along that spectrum without being too tangential." That might seem daunting, but with the right attitude and collaboration, the learning happens horizontally and vertically, says Yue. "We cannot expect our students to be experts in every field. However, we do encourage them to be collaborative, just as we are as faculty," he explains. "Aaron Ames and I have students in control and machine learning who are working together. It is a very fruitful partnership because they're learning from each other by doing together."

The study of autonomy is also a healthy arena in which to nurture the student-advisor relationship, Yue adds, particularly in the CAST setting. "I am very honest with my students. If I make assumptions about strategy that end up falling flat, then I say so, and we learn together," he says. "Questions like the ones we're posing in CAST help students realize that they really need to take the initiative for their own career development, which is beyond any advice I could ever give them." Joel Burdick—who, as senior faculty, is familiar with the complex relationship between risk and reward—likewise makes sure that his students understand he's not exempt from making mistakes, especially in relation to his CAST projects for the Guardians moonshot. He says, "I tell my students, 'I don't know any more than you do, I've just been at this game longer. Let's make the mistakes together, and let's all keep an eye out for where the opportunities are.' There is huge opportunity in autonomy right now."

Each of the CAST moonshots aims to augment or improve the human experience. With that comes a particular awareness of the anxiety associated with shifts in the economy, labor market, and society that will accompany the future proliferation of autonomous systems.

Yue reminds us that adjusting to autonomy is not new: "It just gets refined every five to ten years. What used to be an autonomy milestone is now routine and would be more defined as 'automation'—not autonomy as we think about it at CAST, but the idea is the same. We do not stop progress, and progress has always produced anxiety and debate about how to best integrate and adapt in a new tech era." Many of the coming transitions will be complicated, but the researchers are optimistic. "Human creativity is one thing we can count on," Yue offers. "As some jobs go away, new ones take shape. It's up to our whole society to align educational training and experience to the job market that will emerge in a more autonomous world."

And there will be a wide range of beneficial improvements in that more autonomous world. Caretakers and families stand to gain considerably from the advances that may emerge from the Partners moonshot. Achieving the Partners goal of having a robot walk the dirt, snow, and mud of the Pacific Coast Trail will propel the work of Ames and Burdick as they develop prostheses and exoskeletons for the paralyzed. The prospect of smarter prostheses and vastly improved mobility is a big driver for both researchers. "Christopher Reeve had a devastating injury, and he lived for a long time with a good quality of life. That is wonderful, but you shouldn't have to be wealthy to get that level of care and assistance," says Burdick. "Aaron Ames and I both work on new technologies coming online that will enable services for patients living with severe injuries in a more affordable way, which will directly improve life for some of our most vulnerable citizens and their families." Ames's enthusiasm is palpable when he talks about the progress being made and the possibility it brings. "It's really incredible and powerful to see," he says. "We are working with a startup that uses our walking controllers on their exoskeleton device to realize the first dynamic walking for paraplegics—paraplegics who walk, dynamically, without crutches. You can see how, with these collaborations, with Joel's work on stimulation of the spinal cord and interfacing with the device, and with Yisong's on providing some of the flexibility of machine learning for robotics, the potential gets seriously exciting."

It is important to pair this optimism with a focus on inclusion, participation, and education to ease the coming adjustment to a more autonomous world, says Anandkumar. As a scientist, she believes that communicating the power of partnership is the only way to handle this transition responsibly. Corporations, civic leaders, policy makers, scientists, and educators have to work together to shape the economy of the future and create an informed, engaged citizenry and a more resilient society. "We must all do a good job explaining the benefits of new technologies to the general population. This will help policy makers be as mindful as possible in the coming transition," she says. "It is important that we welcome all people, at every level of the economy, to participate. You do not have to be a computer scientist to learn about the benefits of artificial intelligence; a lot of the time you just have to be willing to engage with new technology. Let's design curricula for non-science majors that teach the important skills of exposure, adaptation, and retraining so the next generation can be comfortable with change. It's the one thing we can count on."

Aaron D. Ames is Bren Professor of Mechanical and Civil Engineering and Control and Dynamical Systems. Animashree Anandkumar is Bren Professor of Computing and Mathematical Sciences. Joel W. Burdick is Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Bioengineering and Jet Propulsion Laboratory Research Scientist. Soon-Jo Chung is Associate Professor of Aerospace and Bren Scholar and Jet Propulsion Laboratory Research Scientist. Morteza Gharib is Hans W. Liepmann Professor of Aeronautics and Bioinspired Engineering; Director, Graduate Aerospace Laboratories; and Director, Center for Autonomous Systems and Technologies. Yisong Yue is Assistant Professor of Computing and Mathematical Sciences.

"CAST represents physics-driven autonomy in which scientists and engineers work together to solve open problems that involve complex physics such as fluid flows and fast dynamics."

Soon-Jo Chung, *Associate Professor of Aerospace and Bren Scholar; Jet Propulsion Laboratory Research Scientist*

Left to right: Dr. Issa Nesnas, Professor Soon-Jo Chung, and students Rebecca Foust and Yashwanth Kumar Nakka in the near-frictionless environment at the CAST space robotics lab