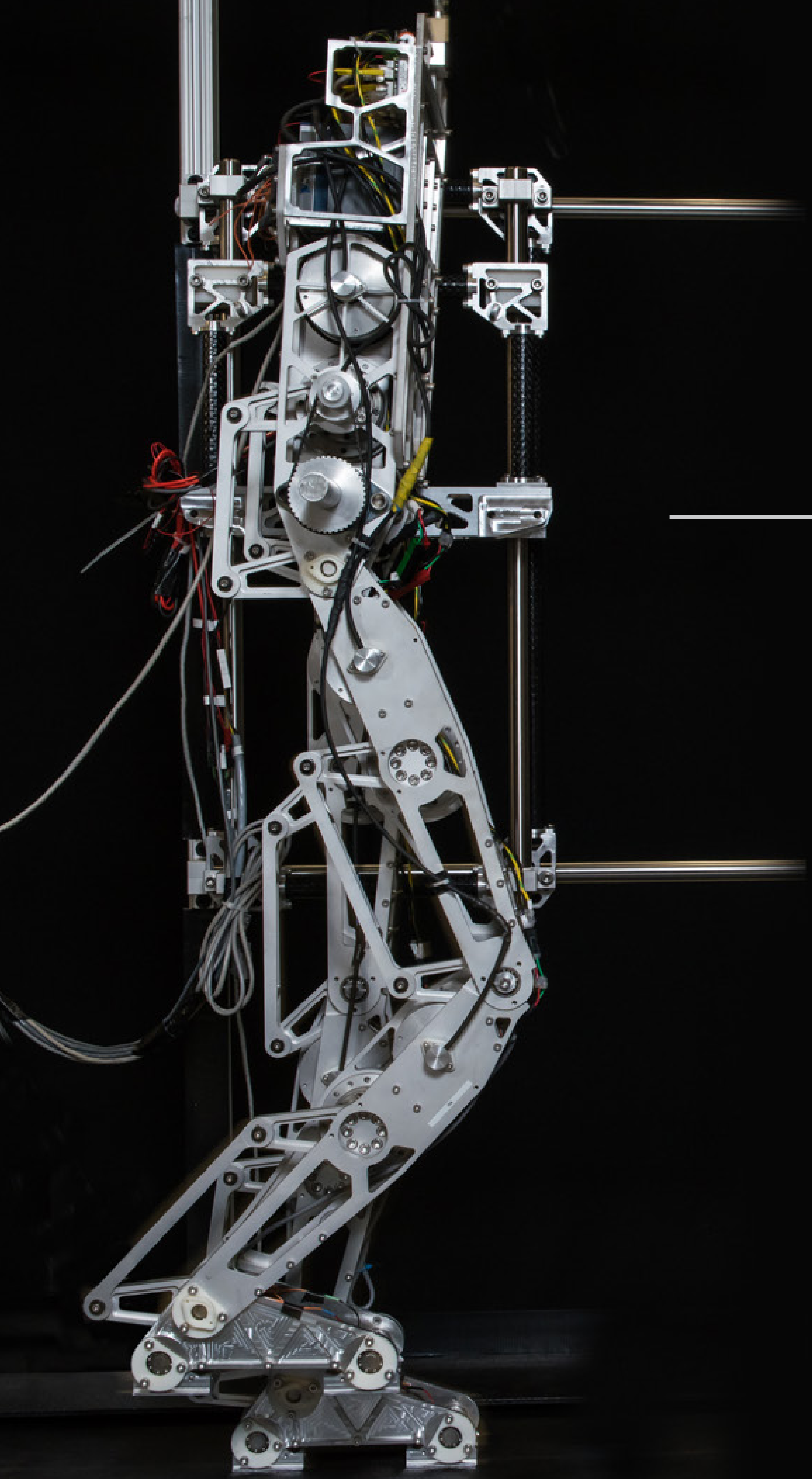
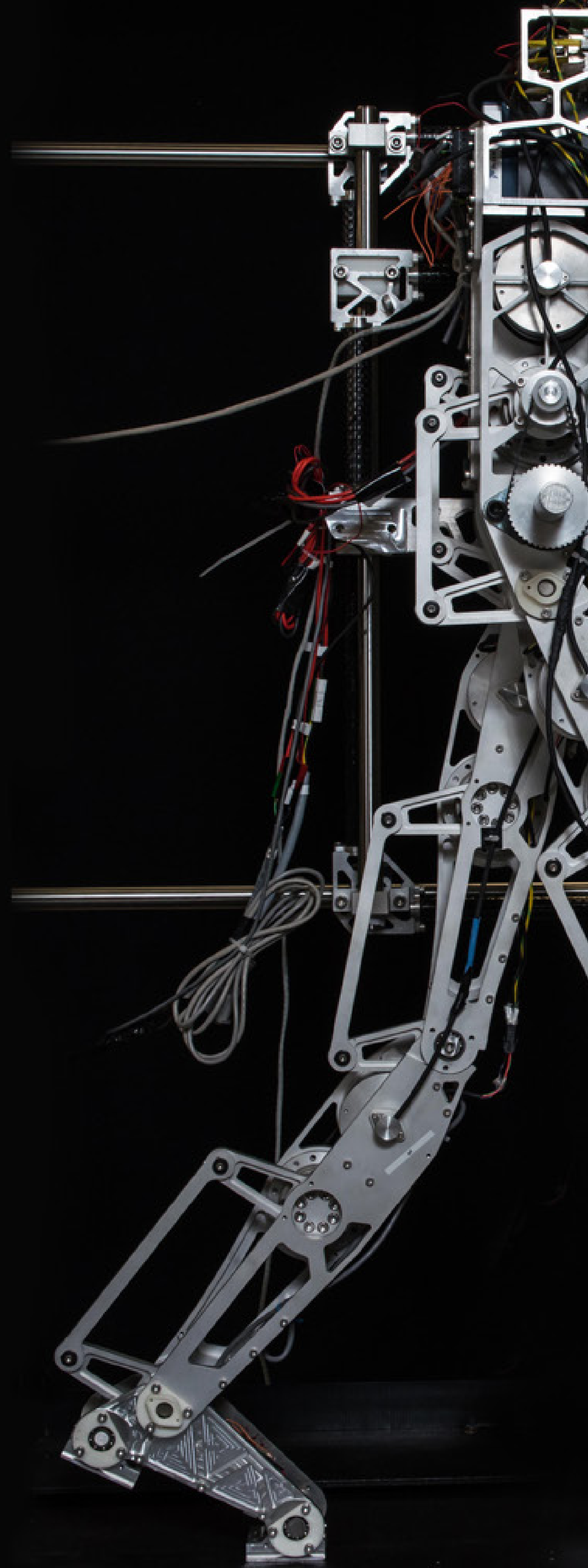


BOTS ON THE MOVE

by Lori Oliwenstein & Robert Perkins

In Caltech labs, robots stride gracefully on treadmills and fly with the complex agility of bats. The researchers engaged in this pioneering work—two of the Institute's newest faculty members—are finding solutions to societal problems while seeking fresh insights into the most basic mechanisms of locomotion and flight.



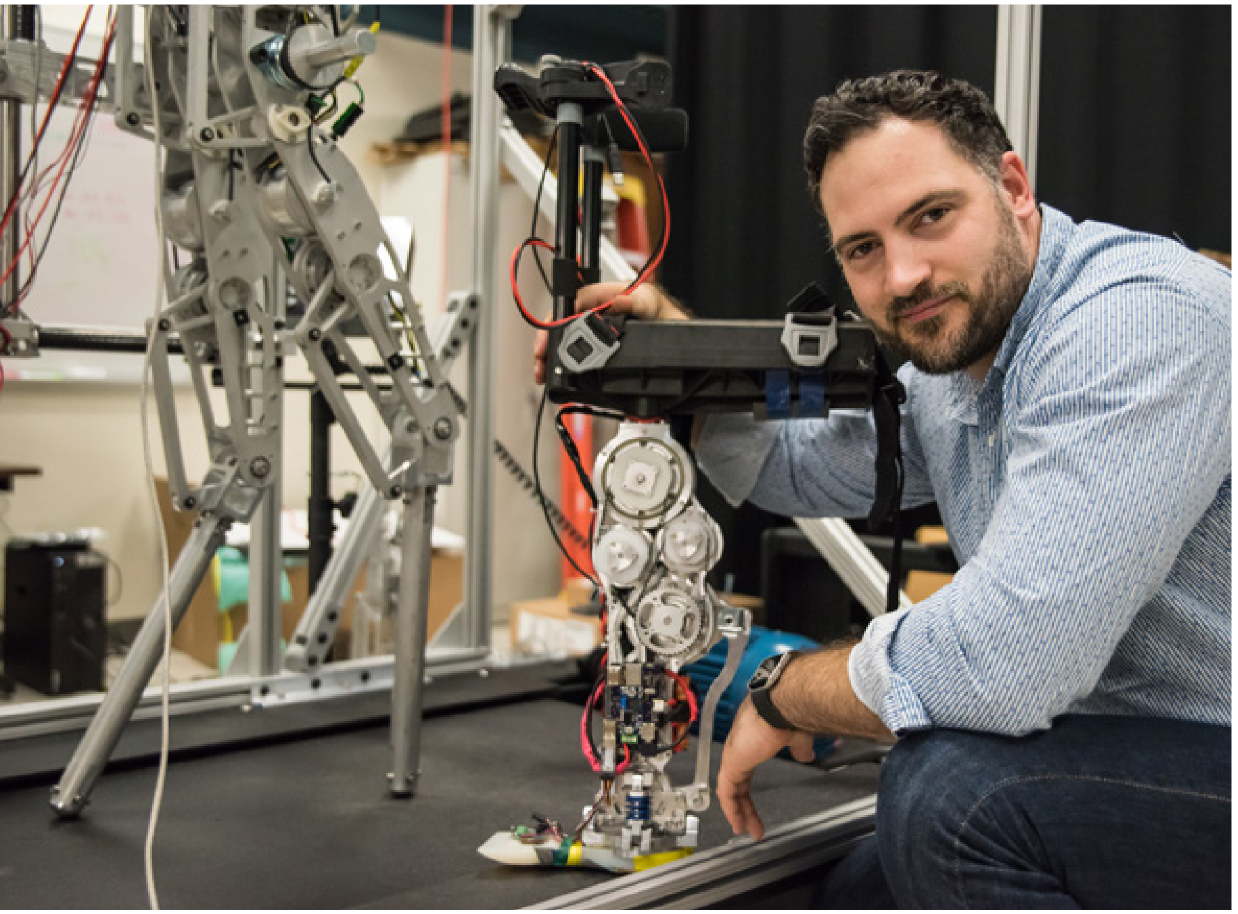
Aaron Ames's new lab at Caltech, which opened for business in mid-August, might strike a first-time visitor as part health club, part machine shop, and part museum. The latter is thanks to a bank of windows that runs along the entire basement hallway in which the lab is situated, giving passersby a glimpse of whatever intriguing robotic experiment is currently underway. Its health-club aura comes from the long treadmills upon which a headless, armless robot walks, automatically adjusting its stride as the speed of the treadmill changes. And then there are the workbenches strewn with custom-machined robot parts and electronics—a far cry from the beakers and air hoods of a conventional laboratory.

That's what it looks like. But what it is, simply, is a robotic wonderland. Especially if the kind of robot you're interested in is the kind that moves. Or, to be more specific, walks. Because Ames focuses the bulk of the time and energy of his Advanced Mechanical Bipedal Experimental Robotics (AMBER) Lab on building, testing, and—most importantly—understanding walking robots.

He does it for the most practical of reasons: to build prosthetics that can help their users achieve the most efficient and effective gait possible. But he also does it for the most theoretical of reasons: to understand how you can create a powerful and smooth gait while keeping a robot upright. In other words, to understand how walking works.

"To me, walking has always been this really special phenomenon because it's a deceptively simple thing," Ames notes. "I often say that walking is simplicity on the far side of complexity. What the human system has to do is so incredibly complex—but in the end, a smooth, natural motion flows out, and I want to understand how to do that in robots. How do you take all of this math, all these algorithms, all of these bits and ones and zeroes, and make a fluid, elegant motion? So that's what's driven me for a long time, and I've finally gotten to the point where all of these things start to intersect—the math, and the hardware, and the application on physical systems."

Of the three, however, Ames puts the math above all else. "Doing mathematics—and understanding why things work the way they do—is the only way to make fundamentally impactful contributions," Ames says. "I 'do' robots, but really, I don't do robots. What I actually do is math, and put it on robots. Robots are the expression of the mathematics."



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While most people take a more standard approach to robotics—the version in which "it doesn't matter how we do it, if the robot does what we want in the end," Ames says—he is all about the process.

"Don't just start putting stuff together without understanding what it means, and how the pieces fit," he counsels. "Start first with the math. Start at that fundamental level, and then work your way up in complexity. I think that makes it easier, because when you finally get to the hardware and you finally get to the robot, you understand why it's doing what it's doing. And, more importantly, you can take that understanding and apply it to lots of different platforms and to a lot of places you wouldn't expect."

There are the prosthetics, for example. Ames has developed a powered prosthetic leg that, like that of its robotic counterparts, automatically senses how fast its wearer is walking and compensates its stride to match. It even has a flexible ankle with two degrees of freedom—the same as a human ankle—allowing for a natural and fluid gait. And there are the walking robots, to which Ames teaches bipedal motion using computational approaches. The robots "learn" their stride in real time, using optimization algorithms to decide how best to articulate their legs in order to walk with the greatest stability and the lowest expenditure of energy. He's even translating these ideas to exoskeletons with the goal of crutch-free dynamic walking for paraplegics and robotic assistance for a variety of mobility impairments.

"The same methodology has been applied to cars for autonomous driving applications, and to swarm robotics, to quadrotors, to flying robots," Ames notes. "Once you get that basic math, you can apply it to a lot of different application domains."

Watch Aaron Ames talking about his work at magazine.caltech.edu/post/bots-on-move

A Home for CAST

The new facility that will house Caltech's Center for Autonomous Systems and Technologies (CAST) will be a place where machines and researchers both work together and learn from one another. While engineers construct and test drones, robots within CAST itself will help run the facility—all while being observed by 46 cameras that will provide complete coverage of the interior, tracking each robot's motion down to within 20 microns (less than a human hair).

CAST will unite engineers, geologists, medical engineers, doctors, rocket scientists, and more, all working in the fields of drone research, autonomous exploration, and robots in medicine. Their goal: to teach autonomous systems to think independently, preparing them for the rigors of life outside the lab.

The facility will have an assembly lab, an oval track for the testing of walking robots, and, as its centerpiece, a three-story-tall, wholly enclosed aerodrome in which the researchers will test flying drones. To provide the ever-shifting environmental conditions that the drones would face in the real world, this aerodrome—the tallest of its kind—will include a 100-square-foot wall consisting of 1,296 fans capable of generating wind speeds of up to 44 mph and a side wall with an additional 324 fans. Each and every one of these 1,620 fans will be able to be individually controlled to create a nearly infinite variety of wind conditions—from a light gust to a stormy vortex—to which the drones will learn to react.

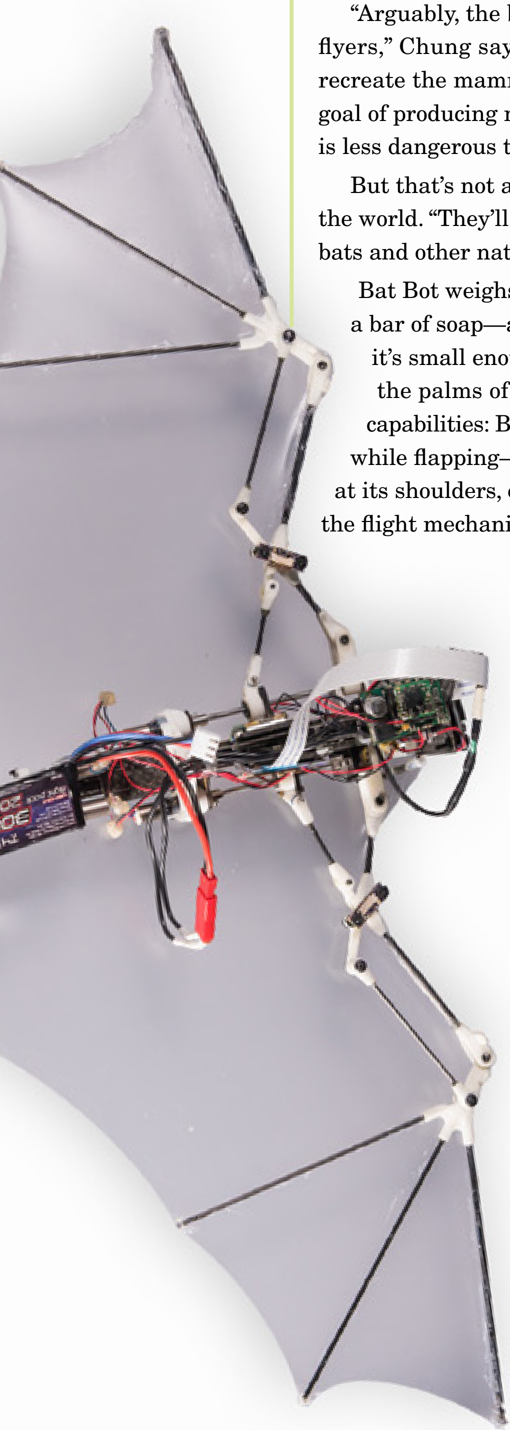
The new CAST facility is slated to open this fall.

Flying Robots

While Ames focuses on ground-based locomotion, Soon-Jo Chung is reaching for the skies ... and the stars. Not with a plane or even a conventional drone, but with a robotic bat equipped with soft, articulated wings, which he developed alongside colleagues at the University of Illinois at Urbana-Champaign, where he had been a faculty member in aerospace engineering for seven years, before joining Caltech in the summer of 2016. That bat—dubbed Bat Bot by the team that created it—is capable of recreating, with what they say is unprecedented fidelity, the complex wing motions and key flight mechanisms of its living counterpart.

"Arguably, the bat is one of the most advanced animal flyers," Chung says. That's why, he says, he decided to recreate the mammalian bat in robotic form, with the goal of producing mechanical flyers that are safe—a wing is less dangerous than a rotor—and energy efficient.

But that's not all Chung's Bat Bots will be able to offer the world. "They'll also give us more insight into the way bats and other natural flyers fly," Chung says.



Bat Bot weighs only 93 grams—about the same as a bar of soap—and has a roughly 1-foot wingspan; it's small enough, in other words, to be cradled in the palms of your hands. But its size belies its capabilities: Bat Bot can alter its wing shape—even while flapping—by flexing, extending, and twisting at its shoulders, elbows, wrists, and legs. This mimics the flight mechanism of biological bats, which involves several different types of joints that interlock bones and muscles, creating a musculoskeletal system capable of movement in more than 40 directions.

The skin on Bat Bot's wings, says Chung, is almost as important as the wings' shape-altering abilities. "The dynamics of bat flight are even more complex and elegant because of the bat's soft membrane wings," he notes.

And so Chung and his team decided to try to recreate those wings in Bat Bot to the best of their technological abilities. The problem, they found, was that conventional lightweight fabrics, like nylon and Mylar, are not stretchable enough to take on the demands of bat flight. And so, the researchers custom developed an ultrathin, silicone-based membrane—a membrane just 56 microns thick, the thickness of a human hair—that can stand in for true bat wings.

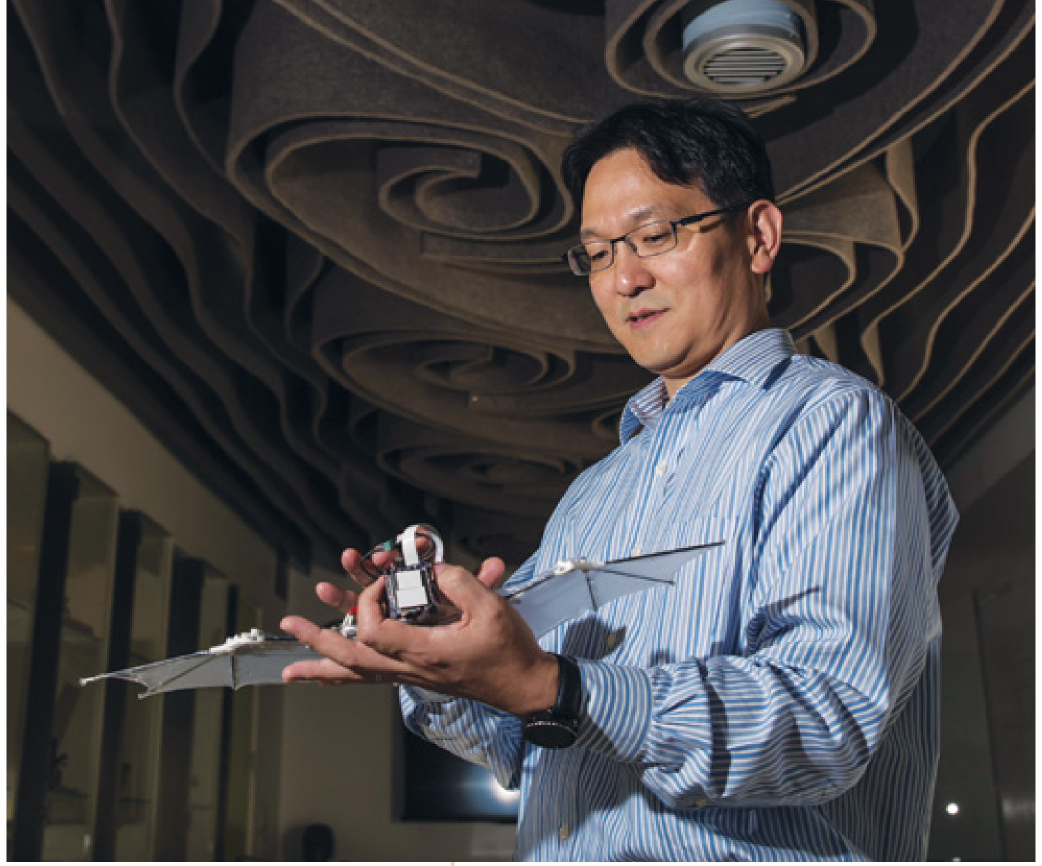
Chung's testing has shown that when a bat flaps its wings, the surrounding air pushes on the wing membranes, deforming them. Similarly at the end of the downward motion of the Bat Bot wings, the membranes snap back to their usual shape by pushing back against that air; this dynamic property of the wings hugely amplifies each flap's power, allowing the lightweight robot to stay aloft with minimal exertion. This same amplification of the power of the wings' motion means that Bat Bot has the potential to be significantly more energy efficient than current flying robots.

Bot bit

The Caltech Robotics Team took first prize at 2016's International RoboSub Competition against 47 competitors. The team's entry, nicknamed Dory, successfully navigated an obstacle course with tasks that required it to touch buoys, fire torpedoes at targets, and rescue an object under water—all autonomously. To see RoboSub in action, visit **breakthrough.caltech.edu/magazine/2017-jun/#First-Place**.

Bot bit

A modular space observatory proposed by Caltech's Sergio Pellegrino would feature a 100-meter mirror—40 times larger than Hubble's—whose components would be shipped into space separately and then assembled onsite by robots. The design calls for more than 300 deployable truss modules that would unfold to form a scaffolding on which small mirror plates would be placed to create a large segmented mirror.



Soon-Jo Chung and his team have created a robotic bat equipped with soft, articulated wings, which has been dubbed Bat Bot.

Watch Soon-Jo Chung explaining his Bat Bot at magazine.caltech.edu/post/bots-on-move

From its skin to its articulated wings, Bat Bot is unique among its flying-robot kin. "I wanted to challenge the status quo of drones that predominantly use high-speed rotor blades, which are quite noisy and dangerous," Chung says. Because of its soft wings, Bat Bot will potentially be useful in environments where more traditional drones, with their spinning rotors, are likely to collide into objects or people, and cause damage or injury.

Bat Bot is not Chung's only focus. He is also working on autonomy and guidance, navigation, and control of spacecraft systems, such as spacecraft swarms, as well as exploring the potential of drone swarms. "You can reconfigure your swarm system to another shape quite easily; think about autonomous flying LEGO blocks that can build whatever you imagine," says Chung. "Also, the entire system doesn't fail even if you lose a handful of individual robots from the swarm. In essence, swarms are more flexible, more robust, and possibly more capable than a monolithic system."

His vision of the robots of the future—whether they are batlike or not—is one in which we as a society think outside the box ... or the paved road. Take, for instance, autonomous vehicles. "Why should self-driving cars be restricted to a two-dimensional world?" he asks. "It might be technologically easier to achieve a fully autonomous flying-car network than to add self-driving cars to the existing roads since there is no gridlock and there are no pedestrians in the sky."

Bot bit

Caltech's Andrew Thompson is working with researchers at JPL on artificial intelligence systems for robotic submersibles to help them track signs of life beneath the ocean's waves. The team hopes this artificial intelligence will someday be used to explore the icy oceans believed to exist on moons like Europa.

Aaron Ames, Bren Professor of Mechanical and Civil Engineering and Control and Dynamical Systems, moved the Advanced Mechanical Bipedal Experimental Robotics (AMBER) Lab to the Caltech Division of Engineering and Applied Science from the Georgia Institute of Technology. He was a postdoctoral scholar in control and dynamical systems at Caltech from 2006 to 2008. His robotics research is funded by the National Science Foundation Cyber-Physical Systems Program and the National Robotics Initiative.

Soon-Jo Chung, associate professor of aerospace and Bren Scholar in the Graduate Aerospace Laboratories of Caltech (GALCIT), splits his time between Caltech's campus and the Caltech-managed NASA Jet Propulsion Laboratory (JPL), where he is a research scientist. His work on flying robots and spacecraft has been funded by the National Science Foundation, Air Force, Navy, Army, NASA, and JPL.