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SPACE DRONES!

Meet NASA's New Mars Copter

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Everyone's talking about private industry getting humans on Mars. Mars trips! Mars houses! Mars colonies! But no one's going anywhere without the help of one brilliant, peculiar, fantastical space center—NASA's Jet Propulsion Lab, which is behind almost every amazing first in the history of space travel.

By Jacqueline Detwiler

Photographs By Koury Angelo

The 177-acre campus of NASA's Jet Propulsion Laboratory has been there since 1936, after a few students from the nearby California University of Technology started testing rockets in their dorm rooms.

The Right Kind of Crazy

August 2012

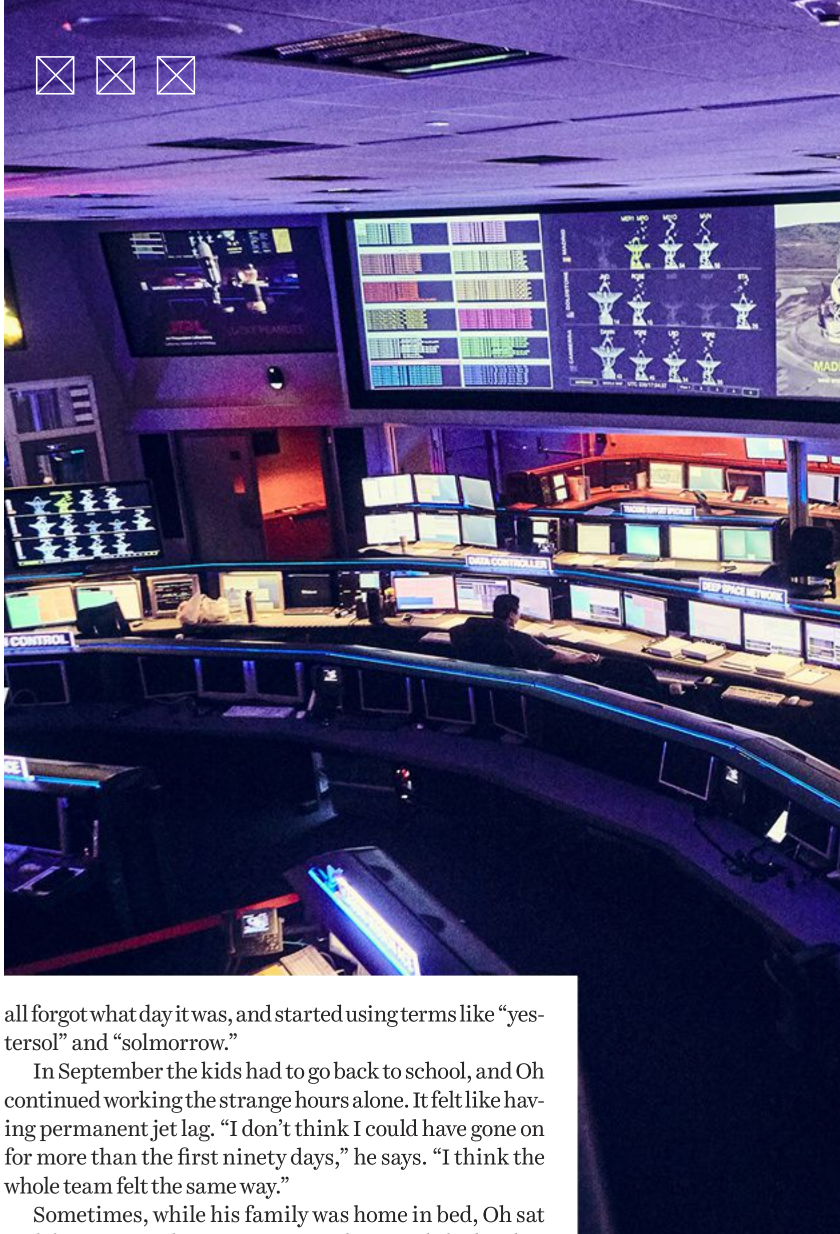
AT 2:00 A.M. in the blond hills of La Cañada Flintridge, California, one house stands lit among the others—an open eye in a sleeping town. Bryn Oh, the woman who lives in the house, helps her son Devyn, eight, walk his bike to the parking lot of the high school across the street. Devyn, who just learned to ride, wobbles for a few minutes before pedaling furiously out into the darkness, letting off a whoop as he gets going. Bryn's older children, Ashlyn, ten, and Braden, thirteen, watch as he goes. David Oh, Bryn's husband and the reason they're all up at this uncivilized hour, isn't there to see it. He'll arrive home around 3:00 a.m., when he gets off work. Tomorrow will probably be closer to 3:40. Bryn has it all worked out on a spreadsheet.

David Oh is an engineer at NASA's Jet Propulsion Laboratory, a 177-acre campus of white buildings that peeks up out of the Angeles National Forest near Pasadena like a fleet of galleons hidden in the hills. He works as the lead flight director for JPL's Mars Curiosity Rover, which landed on August 5, 2012. While the rest of the country is asleep, Oh is often driving the $2.5 billion remote-control car around the Red Planet.

JPL, home to three thousand engineers and five hundred scientists, is very old—2016 is its eightieth anniversary—but it's only in the last few years that the close of the space shuttle program has left enough of an excitement gap for the center's singular brilliance to shine through. In contrast to NASA's other outposts, where you'll find a lot of unflappable pilot types with high-and-tight haircuts, JPL is full of strange, excitable, idea people. Climate scientists who work side gigs as comedians and engineers who shave star shapes into their Mohawks before landings. People like Oh, a cheerful MIT graduate who, along with his wife, switched all the family clocks to Mars time one summer.

In order to keep pace with Mars' light–dark cycle (sols, rather than days), Oh and the rest of the Curiosity staff got up forty minutes later each day than they had the day before. They kept this up for almost three months to ensure that someone was around to fix any problems with the rover during its most vulnerable period.

Bryn, who met David at MIT and is also an engineer, had always been fascinated by the idea of living on Mars time. So when the edict came down that her husband had to work crazy hours, she drew up a Mars schedule on a big mirrored door in the hall. Every "morning," the Oh family would eat breakfast together. David would drive to JPL's dim, theater-like mission-control room to get started, and Bryn would find things for the kids to do—taking them on late-night bike rides, to diners and all-night bowling alleys. When Oh's shifts started to stretch across midnight, they all forgot what day it was, and started using terms like "yestersol" and "solmorrow."



In September the kids had to go back to school, and Oh continued working the strange hours alone. It felt like having permanent jet lag. "I don't think I could have gone on for more than the first ninety days," he says. "I think the whole team felt the same way."

Sometimes, while his family was home in bed, Oh sat with his team in the mission-control room while the photos came down from Mars. These arrived in two to four passes a day, when the rover would lob big chunks of data up at the Mars orbiter to relay down to receivers on Earth, and the computer would render them, line by precious line, on the mission-control projector. Some days all they'd get were black-and-white images, but other days full-color landscapes of ravines and craters and distant mountains would appear, the sun burning off the haze of Mars' thin atmosphere like it was sitting right there in front of them.

"We're the first people ever to see these pictures," Oh would think, looking up at the alien vista.

"This will all be going out to the world tomorrow. But for now it's ours."

August 2016

JUST OFF CALIFORNIA Interstate 210, there are two signs on the side of the road. The bottom one shows an outline of the California mule deer that tend to meander out of the sagebrush and into passing traffic. The top one just says "Space," with an arrow pointing forward. The second sign is not an official

Above: JPL's mission-control room is operational twenty-four hours a day, seven days a week—and has been for the last fifty-two years.

Left: High Bay 1, where spacecraft are assembled, is a clean room that moves air quickly from top to bottom to prevent dust from getting into critical parts of space machinery.

JPL sign. No one really knows where it came from. People around here presume it was put there as a joke and no one ever bothered to take it down.

The people who work at JPL love little inside jokes like this. There are easter eggs sprinkled throughout the campus and family of spacecraft JPL has built. For example: The dots and dashes on Curiosity's wheels are Morse code for "JPL." Engineers slipped them into the plans after NASA said they couldn't put their names on it.

That engineers should be imaginative is not surprising. Engineers are essentially mad inventors with salaries. But to succeed at the kinds of lunatic feats JPL has made possible (Let's fling a satellite at Neptune! And Jupiter! And Saturn!), you can't *just* be creative. You have to be creative and also detail-obsessed and cooperative and a little loony. You have to be the kind of person who would pass a silly joke sign that says "Space, this way" and laugh, but then also narrow your eyes and tilt your head like a collie and wonder whether it might actually be possible to follow the sign to space. What kind of propulsion system it would require, for example. Whether you'd need to use a gravity assist or . . .

Why JPL is a place that attracts people like this is a question HR directors all over the country would love to answer. Maybe it's because JPL works only with robots, never humans, so the stakes are low enough to try the really weird stuff. Maybe it's the weather. Maybe it's because, even though the campus is just five miles from the swank suburban enclave of Pasadena, it still seems like the frontier out here—big, clear, open, promising. This area was once called Arroyo Seco—dry riverbed—and is a series of natural launch tubes like a dusty marble run. There is a relentless sense of unstoppableness in the Arroyo Seco. Why couldn't you blast a Volvo to the Kuiper Belt out here? Who, or what, would stop you?

The United States' frontier period ended in 1890, just forty-six years before JPL (which, just for reference here, is currently receiving data from a probe in *interstellar space*) was created. The founders, a group of students from the California Institute of Technology (notably including a guy named Jack Parsons, who looked a little bit like Errol Flynn and may or may not have been assassinated by Scientology founder L. Ron Hubbard) started testing jet-propulsion techniques in their dorm rooms in the early 1930s. When one such experiment blew a hole through a wall, they moved to their current location. This was in 1936. Eighty years ago.

This might seem strange given that NASA itself is a sprightly fifty-eight. Even though JPL is currently beholden to its parent organization's budgets and approvals, it is actually the reason NASA exists. In the forties, the U.S. Army requisitioned the ragtag band of space cowboys to study Germany's V-2 rocket program and develop jet-assisted takeoff for Army planes. It wasn't until the Soviets launched Sputnik in 1957 that the lab really turned to space: The Army gave them a three-month deadline to get an American satellite into orbit. When they pulled it off, Congress created NASA, and the Army handed over its jewel in the California canyons.

In its new role—nonprofit, Caltech-affiliated, NASA-funded, civilian-controlled—JPL became a center for the most insane, creative engineering on earth. It focuses solely on robotics: relay systems of mirrored satellites, titanium

JPL: THE GREATEST HITS

1958
Explorer 1, the first satellite launched by the United States, kicks off the space race.

1977
Voyagers 1 and 2 are sent to explore Jupiter, Saturn, Uranus, and Neptune. And they're still going. The probes have continued farther into space than any other man-made object in history.

1997
The Cassini-Huygens unmanned spacecraft is launched. Cassini became the first space probe to enter Saturn's orbit, while the Huygens lander gathered data from Saturn's moon, Titan.

2011
The Mars Science Laboratory opens with the goal of studying Mars and preparing to send humans there. MSL successfully landed the Curiosity rover on Mars in 2012.

2011
The Juno space probe is launched from Cape Canaveral. It reached Jupiter's orbit this summer and will collect data about the planet's (and our solar system's) origins.

space scouts, and carbon-fiber rovers that visit other planets years—sometimes centuries—before any human could be expected to arrive. NASA calls JPL a federally funded research and development center, which means, essentially, that NASA pays for JPL, but JPL can do whatever the heck it wants. It's a bureaucratic unicorn. NASA's Google X.

Compared to a place like Google X though, which has a notoriously high tolerance for failure, JPL has been enormously successful. Between 1958 and 2012, twenty-three of the thirty-eight spacecraft JPL built succeeded in their missions—often with the entire public watching. In 1977 JPL sent the twin Voyager probes on flybys to the end of the solar system. They're still going. In the early 2000s, it landed two rovers with wheels on Mars in a row at a time when the Red Planet had a record of demolishing 60 percent of the spacecraft it encountered. This July, the agency slid a satellite into a loping, radiation-protective orbit around Jupiter while 1.5 million people watched online.

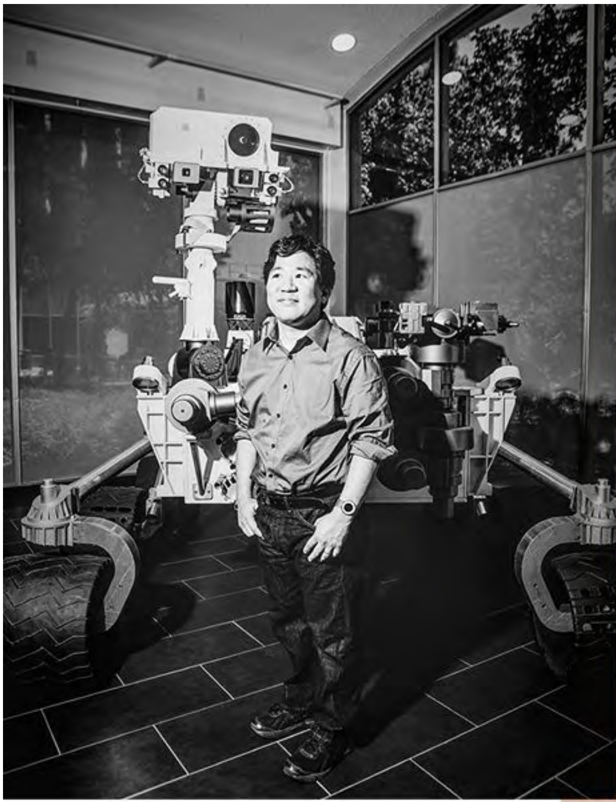
These days, JPL has its fingers in so many space gizmos that even the director, Michael Watkins, who succeeded longtime director Charles Elachi when he retired in June, isn't sure how many are out there. "Oh my gosh, do you know?" he asked JPL's longtime publicist when I inquired. "There are nineteen currently flying, and then there are another ten that are in development. The way we count is kind of . . . you don't include anything that flies on craft that aren't ours . . ." He opened his hands in a gesture that clearly indicated complexity.

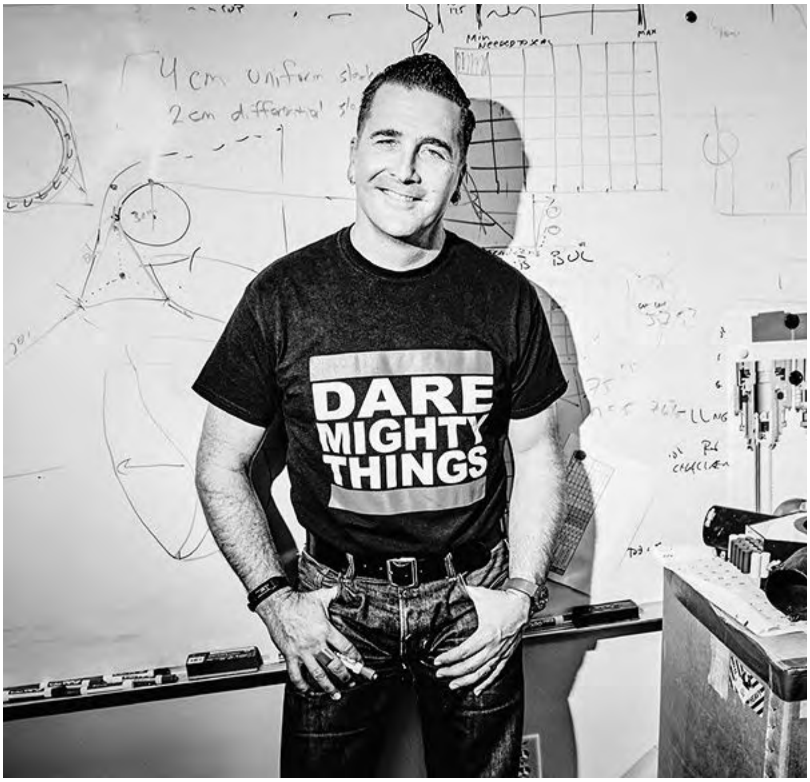
The best way to understand what JPL does is to consider the center's "directorates," which is space-agency-speak for departments. Among these are four organized by planet. Taken together, they sound like a particularly difficult round of *Jeopardy*: Earth Science, Astrophysics, Mars, and Planets That Are Not Mars.

Earth Science, which most people don't know NASA even does, employs space- and air-based measuring tools to study topics like ice melt in Greenland. Astrophysics locates potentially life-bearing planets in the deep solar system using telescopes and advanced math. Mars is fairly obvious, and Planets That Are Not Mars is a grab bag of loony, exciting, comic-book stuff. Missions to explore places like Enceladus, an ice-covered moon of Saturn whose water geysers spout so high they spray miles out into space, and Titan, the only known moon in the solar system with an atmosphere, a frosty aquamarine marble covered in frigid lakes of methane.

JPL allows its employees to switch projects and directorates throughout their careers, to chase engineering dreams or follow a planet they find exciting or whatever. "We try to let the employees pick the thing that suits them best, because they enjoy it more and do better," Watkins says. This is one reason why the people who work here never leave. If you build radar systems, for example, you can go from working on machinery intended to survey Greenland to a telescope that will search the universe for habitable planets to a probe that will attempt to peer through the miles-thick ice crust of Europa, an ocean world outside Jupiter where blind, colorless water creatures may be hiding near hydrothermal vents.

Unsurprisingly, this last mission is part of the Planets That Are Not Mars assortment of plans to visit cool places in space. It's called Europa Clipper, and is expected to launch in 2022. You don't hear about it as much as you hear about SpaceX and Blue Origin trying to get people on Mars though, probably because people find the idea of humans in near-space more exciting than robots in far-space. This is a shame, because Europa is amazing. In addition to containing more water than there is on Earth and being totally encased in ice, there's a not insignificant chance it's full of real, honest-to-God alien space fish. It's the kind of place that still makes the hair on the back of your neck stand up. And if we ever want to know anything about it, we'll have to find out from JPL.





Above left: High Bay Bob the mannequin lives in High Bay 1. He serves as a reference point to show human scale next to the spacecraft, as well as an example of proper clean-room attire.

Above center: Adam Steltzner, an engineer on the Mars 2020 project, played bass in a rock band before earning his Ph.D.

Above right: A model of the complicated Sky Crane maneuver. Only so many tests can be done on Earth before a spacecraft must stand on its own.

Left: Lead Curiosity flight director David Oh and his remote-control car.

ADAM STELTZNER and I are standing in the air lock outside Room 233-140 in hairnets, gloves, hospital masks, and booties, as well as full-body polyester bunny suits with hoods and moon boots that clip around our shins. A dozen nozzles blast us with air to remove dust. We're about to enter an ISO Class 5 laminar airflow clean room, where technicians are building the propulsion system for Mars 2020—the follow-up mission to the Curiosity rover.

Steltzner is one of a couple engineers at JPL who have become semi-public figures on account of their defiant strangeness. Their JPL-ness. He played bass in a rock band for years before going back to school to earn his Ph.D. Under his bunny suit and hood is a shirt that says "Whiskey and Yoga." Three earrings, full sideburns, and a turquoise ring the size of a postage stamp complete the look. He talks about his work in freewheeling, anecdotal paragraphs that include a lot of film and music references. When asked how it is that he's been part of so many cool space projects: "I'm like a Zelig of cool experiences. I was in Prague the first time they celebrated the Prague Spring and Havel was there and the Rolling Stones were playing and they had these tanks turned over and it was raining…"

Before Steltzner started working on the entry, descent, and landing system of Mars 2020, part of which is being built in this room, he ran the team that built the landing system for Curiosity, the rover David Oh drives. JPL affectionately calls the Curiosity landing the "seven minutes of terror," because it took seven minutes to bring the rover from speeding orbit to a gentle halt on the planet's surface. They knew the rover would be so far from Earth when this happened that there could be no communication during the difficult parts. Everything had to be automated in advance: when the heat shield popped off, when the parachute deployed, when the reverse rocket thrusters fired. They had to consider the weight of the rover, the density of the Martian atmosphere, the approach angle, power source, torque, inertia, speed.

This is just engineering. But, and here's the difference between working at JPL and working anywhere else: A spacecraft has to be perfect. Because machines like Curiosity and Mars 2020 are some of the most complicated things *ever created by humans,* when JPL runs into a problem, there is no one to ask for help. You're on your own.

For Curiosity, the big problem was the final touchdown on Mars. The rover, at two thousand pounds, was too heavy to employ any of the systems JPL had used to set down spacecraft in the past. Airbags and parachutes couldn't handle it alone. Without a completely new landing strategy, they'd send the rover fifty million miles just to bash it open on a rock, and that would be that.

So JPL held a brainstorming session. About a dozen people who had worked on all the various Mars landings came. They went back and forth over a couple of days, and then all at once, the group figured it out. "It was one, beautiful, glorious moment," Steltzner says. People exclaimed and stood up and wrote on the whiteboard and talked at once. They had an idea: Fly the lander where you want to put the rover down, and then lower the rover on a rope, they said. A rope. Yes, a *rope.*

They called the technique the Sky Crane maneuver. Everyone thought it was crazy. The director of NASA said it was crazy. But no one told Steltzner, "You want to lower a $2.5 billion Mars rover from a flying base on a rope? What kind of idea is that? How did you even get this job?" Because the idea came from JPL, and JPL has historically been successful at performing ludicrous feats of interplanetary engineering, NASA let them do it. And it worked. The Sky Crane maneuver worked so well that it will be the system used to lower Mars 2020. A video of the seven minutes of terror is now part of JPL's two-hour public tour.

The top brass at JPL love the Sky Crane maneuver because it's a perfect example of the way the creative ecosystem here is supposed to work. There was pressure on the engineers to hit their deadline but not the strain of overwork and overmanagement that plagues most companies. There was an anti-bureaucratic willingness to consider quirky ideas. And then NASA trusted Steltzner's team enough to let them try something that was unproven. It was the most JPL of JPL moments. Steltzner even wrote a memoir/business-advice book about the Sky Crane design process called *The Right Kind of Crazy*.

Of course, Mars 2020 has a new problem. It's a sampling rover, which means it will be the first Mars vehicle to bring test vials to the Red Planet, fill them with rocks and soil, and seal them to await return to Earth on a future mission. In order to do this properly, these vials cannot be contaminated by anything—bacteria, viruses, human DNA, cologne. Nothing. They have to be cleaner than the cleanest operating room. "We could not have gone into the clean room if these things were being assembled today because I have gel in my hair," says Steltzner. "When you get down to the level of cleanliness required for some parts of this spacecraft, there are only certain shampoos you can use."

NASA has a planetary protection group that delights in creating protocols for processes like these. NASA *loves* protocols. JPL, as you might imagine in an organization formed by rogue students in the desert like some kind of Burning Man installation, does not. And anyway, the current regulations aren't rigorous enough to keep the Mars 2020 vials clean. To ensure that the measurements they'd be taking would be trustworthy, Steltzner and his team had to break with a forty-some-year tradition of NASA planetary protection policy to create newer, better protocols.

"It has caused some, ah, administrative friction," Steltzner says, with no small amount of glee.

THE MOST EXCITING project happening at the Jet Propulsion Lab right now isn't a satellite flying by an ice planet. It's not even Mars 2020's incredibly clean specimen collection. It's a helicopter. If NASA grants official approval, sometime in the next month or so, Mimi Aung, project lead on the incipient Mars Helicopter mission, will send the machine up on the Mars 2020 rover as a stowaway, a barnacle on its hull. Once the rover lands, about seven months after takeoff, the copter will zoom ahead of the rover every morning, taking high-resolution photos as detailed as those in Google Maps.

"So I think you know this," she says, cuing up PowerPoint slides like she's about to give a presentation on market dynamics. "But allow me to state the obvious: Humans have never flown an aerial vehicle anywhere outside our own atmosphere. Not balloons, not planes, not helicopters, nothing," she says.

Aung is going to be the first.

The helicopter Aung and her team have developed has been in the works for years now, ever since JPL's former director went on a lab tour and saw a bunch of quadcopters

HOW IT WORKS

The Mars Copter

JPL's latest remote exploring device is the next quantum leap in space exploration. Here's what makes it different from an Earth drone.

Earth

Blade speed: 450 to 600 rotations per minute
Weight: The FAA considers anything between 0.55 and 55 pounds a drone. The DJI Phantom 4 pictured here weighs 3.04 pounds.
Flight time: 28 minutes
Traditional helicopters have a vertical rotor on the tail to cancel the torque created by the main rotor. Otherwise the cabin would spin around in circles. Two of the four rotors that power a quadcopter such as the Phantom 4 spin the opposite direction in order to cancel out torque and enhance stability.
Partially autonomous: Drones rely on GPS and radio waves to communicate with a controller operated by a human.
Powered by: Batteries

One prototype of the Mars helicopter used PVC tracking balls and cameras to fly itself.

ILLUSTRATIONS BY SINELAB

Mars

Blade speed: 2,600 rotations per minute
Max weight: 3.08 pounds
Flight time: Two to three minutes
The Mars helicopter is coaxial: It has two horizontal rotors right underneath each other that spin in opposite directions to cancel out torque. JPL chose this formation because it will minimize the copter's weight and volume.
Fully autonomous: A gyroscope, accelerometer, a camera, an altimeter, and an onboard computer fly the drone themselves.
Powered by: Solar cells

Mimi Aung, project lead on the Mars Helicopter, is creating the first aerial vehicle to be flown outside Earth's atmosphere.

sitting in a research bay. Aung was on the bus when the director turned and said to one of JPL's other managers, "Hey, why don't we do this on Mars?" That was all it took. They resurrected some old research and got to work.

The Mars copter works much like drones do here on Earth, only it is very small and very light. It has two sets of shallow-sloped rotors that spin extremely fast—twenty-six-hundred rotations per minute—in order to achieve lift in Mars' atmosphere, which is just one-hundredth the density of Earth's. Helicopters, in contrast, achieve lift just by moving heavy air at a maximum of six hundred rpm.

You would be forgiven for thinking, at this point: Okay, that sounds easy enough. We already know how to fly drones. How much harder could it be to fly one on another planet? A Mars drone seems so natural an outgrowth of the rover missions and JPL's aeronautics expertise that it can make you forget what Aung and her team are really up against. The entire field of aeronautics is based on *air*.

"A lot of people simply didn't even believe we could fly this thing," she says. "Some people said, 'Show me.' And so that's what we did."

On the surface, Aung does not possess the trappings of strangeness you find in some other employees at JPL. She dresses simply—blouses, skirts, pants. Her hair is brown. She speaks matter-of-factly about meters per second and onboard guidance and incremental tests. But still, the obsession is there. When she watched *The Martian* last year, all she could think about was how much she wished Mars' atmosphere was thick enough to create a storm like the one that strands Matt Damon on the Red Planet. "I was sitting in the theater coveting that atmosphere," she says.

While none of their solutions are as bizarre as the Sky Crane, Aung and her team are up against challenges at least as formidable as those Adam Steltzner faced. The first time they tried to actually fly their new invention, in a big tent where they had reproduced Martian atmospheric conditions, they flew it into a wall. The video of the test shows the copter wiggle its way roofward, and then zig and zag wildly before pitching toward the back of the room in a way that makes you wince. "There's a reason we cut the video off at that point," Aung says. "The guy controlling the joystick couldn't keep up with it."

What they had failed to realize was that the density of Earth's atmosphere doesn't just provide lift, it also holds helicopters steady. In the thinner air, controls become too reactive and unpredictable for a human being to manage. Now, in addition to weight concerns, energy constraints, ruggedness in case of crashing, barely enough atmosphere for lift, and getting the copter to Mars in the first place, there was another problem: They had to fully automate it. It's as if Henry Ford had to invent self-driving cars.

In order for the helicopter to sense where it was and fly itself, it would need cameras. Bam. Another problem. Though the test room has Mars' atmosphere, it still has Earth's gravity, which means a Mars helicopter stocked with cameras would be too heavy to lift. So Aung and her team thought about it, and they put little PVC tracking balls on the copter and used cameras attached to the walls of the room to fly it. In May, they held another test. Starting up gently, the prototype departed the ground and hovered six feet in the air. It didn't hit anything.

When this technology succeeds—and if JPL's history is any indication, it will be "when" and not "if"—flying around on other planets with atmospheres will be the next platform for space exploration. Imagine the possibilities this will open up. Satellites can create only macro images, and currently a rover can travel only about five hundred feet a day. In some senses, Mars will only become a real, complete place—the way Earth is—when we can see it from the perspective of the sky. After that? Could we send a scout drone to Titan? A boat to Europa? We could be the aliens making first contact in the movies, answering the age-old question of what it is the aliens want: better maps.

Aung is not a person given to self-mythologizing. But if she wanted to, she could really go for it. She was born in the United States to a mathematician and a food chemist, but moved to Burma at the age of two and a half, in 1970, eight years after a military coup there ended democracy and brought with it poverty and human-rights abuses. In Burma, she was happy but very poor. The Aungs lived in a house with a concrete floor, a well for water, and a radio that played only a few times a week. There were no libraries. No television in the entire country. "Back in those days I had no hope. No idea of where I would be today," she says. And then, in one of the great understatements, she says, "The places where I was growing up didn't have a space program." Aung never even knew if she'd ever get on a plane.

Aung's parents managed to secure university positions in Malaysia when Aung was eleven, enrolling her in a British school with more resources. That was Aung's dream—not fame or riches, but libraries, computers, the freedom to dream incredible things and the resources to make them real. A place like an American university, and then a place like JPL.

Aung did so well at the British school in Malaysia that at sixteen her parents sent her back to the U.S. alone. She was the only member of the family born here, so while her two younger sisters couldn't come, she could. She was an envoy—a spore from the next generation seeking newer and better opportunities. Everything she owned fit in a single suitcase. When Aung tells the story, it's at this point that she tears up.

"We're so busy, working hard in this country," she says. "You really don't stop to think about how far you've come." From Burma to the modern edge of the American frontier, for example. From warplanes to satellites to space cars on distant worlds. From lying on a concrete floor dreaming about the future to flying on Mars. PM