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Mars Helicopter Forges New Frontiers

Ingenuity more than lives up to its name, in accomplishments, design, and promise for the future of rotorcraft on Earth—and beyond.

By Paul Koscak

ON APR. 19, 2021, THE HELICOPTER Ingenuity completed the first powered controlled flight on a planet other than Earth when it lifted off the surface of Mars. The historic achievement proves what fearless engineering, inventive designs, and groundbreaking materials can achieve. But the feat is another example of how rotorcraft can be the right ship for the right mission, on Earth and in space, as well.

During its debut flight that April, Ingenuity, also known as the Mars Helicopter, smoothly rose 10 ft., hovered, and then gently lowered its four legs back on the planet's rust-hued soil. More-ambitious flights followed shortly after.

"Truly a milestone in the history of aviation" is how Jim Viola, HAI president and CEO, describes the event. "I look forward to seeing the kind of applications that industry can devise for a helicopter that's capable of flight at 100,000 ft. here on Earth."

Now that Ingenuity has provided proof of concept, future Mars rotorcraft will prove their worth by closing the gap between orbiters and rovers and exploiting the inherent advantages of aviation in the exploration of Mars.

"Orbiters can't resolve surface features less than 3 ft.," notes Ben Pipenberg, lead engineer for the Ingenuity project at AeroVironment, the NASA contractor that designed and built the Mars Helicopter's earlier prototypes and most of the major components of Ingenuity, including its blades and landing gear. "Rovers are good but slow," he says. "A helicopter can cover in a few minutes what a rover covers in a few years."

Birth of a Superstar

To really appreciate Ingenuity's accomplishments, one needs to look behind the scenes at its creation.

Since 2014, numerous prototype helicopters have been built and put through the wringer in punishing tests simulating a rocket's launch from Earth, the unforgiving environment of space, and the harsh conditions on Mars. The need to function in extreme environments drove Ingenuity's design, a project for which NASA budgeted $85 million.

"A rocket launch is a violent event, particularly for a helicopter," Pipenberg says. "There's lots of high- and low-frequency vibration. The helicopter is a pretty brittle piece of hardware compared to the 2,200-lb. rover [Perseverance]," about the size of a compact car.

A delicate aircraft, Ingenuity is just 19 in. tall and weighs about 4 lb. Its two 4-ft. counterrotating blades whisk the ship through a mostly carbon dioxide atmosphere that's only 1% as dense as Earth's. That's like taking off from a heliport sitting atop five Denalis, the highest mountain peak in North America at 20,310 ft., stacked atop each other, or about 100,000 ft. At that altitude, there's hardly any air for helicopter blades to push against.

AeroVironment, a California-based manufacturer of unmanned aircraft systems (UASs), solved that problem by making an advanced, light, super-strong blade for Ingenuity. The blade can withstand the tremendous rotational force needed to generate sufficient lift to fly in the thin Martian atmosphere.

Ingenuity's two counterrotating blades spin at nearly 2,500 rpm, compared with about 370 rpm to produce the same lift on Earth. The blades also feature molded carbon components, a foam interior, and a paper-thin skin of carbon

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Flying From the Right Seat 170 Million Miles Away

When Ingenuity flies, Håvard Grip is at the controls. A NASA research technologist, Grip is the agency's Mars pilot and has been with the program since it began in 2013.

Grip actually helped design and test Ingenuity's control system and points to the many parallels to flying conventional helicopters. Much of his work, for example, centers on aeronautical decision-making.

"We plan each flight," says Grip, who's also a private airplane pilot. "There's overlap to a standard flight plan. You have to know the aircraft and its performance and evaluate the environment."

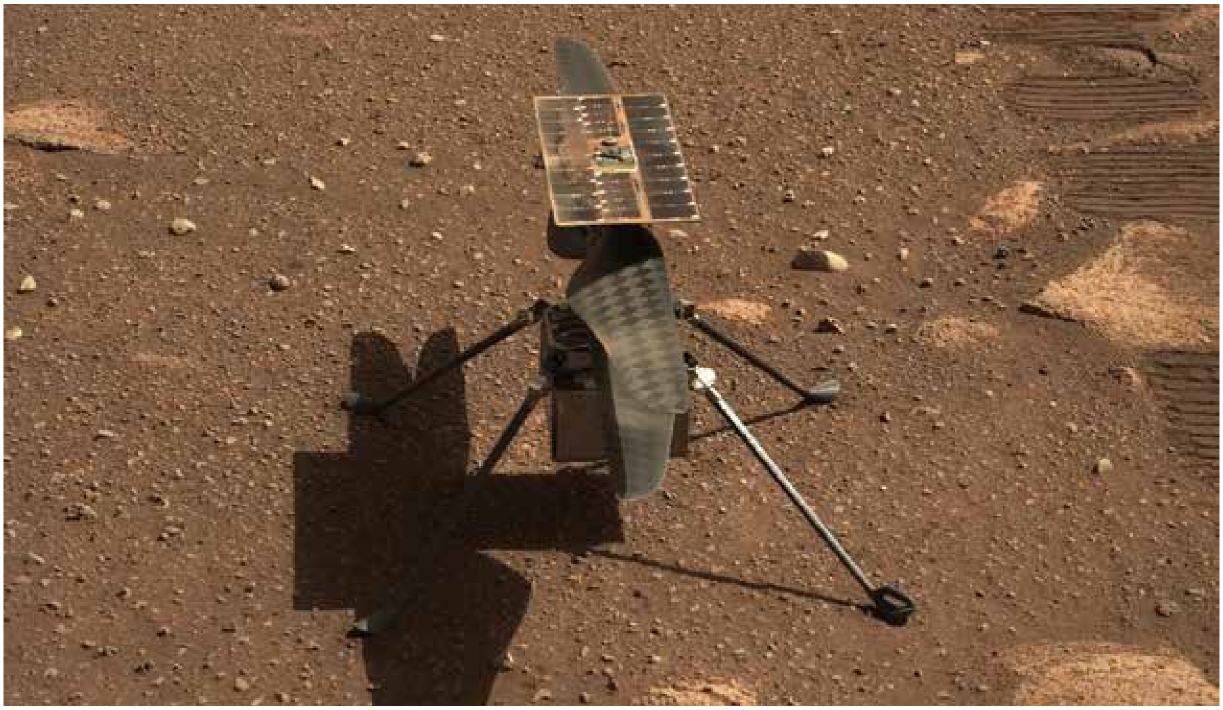
Håvard Grip records data of Ingenuity's first flight into the official pilot's logbook for the project.

Before each flight, Grip goes through a flight risk assessment, just like any other pilot flying on Earth would do. He checks weather, winds, and density altitude. He studies the terrain Ingenuity will be flying over and considers potential landing spots in case there's a problem. He then applies that information to Ingenuity's performance graphs. The graphs show the requirements to accomplish quality takeoffs and landings, how Ingenuity will perform in turns, and how the aircraft will perform at altitudes and distances. With that information, Grip is now able to create a flight profile. The scenario is entered into a computer and shown graphically, or the whole trip can be simulated before it's sent to the Perseverance rover, which then relays it to Ingenuity.

Grip also makes good use of checklists before and after a flight. "We focus on the things that matter, and we have extensive checklists," he says.

As Ingenuity is a technology demonstrator, Grip's role is more test pilot than pilot. Pressing the helicopter toward more-demanding flights is the only way to learn the ropes of flying on Mars. "This is an experimental aircraft, so we're not concerned with staying within the envelope," he explains. "Here [at NASA], we push it."

Because of the radio transmission lag time between Earth and Mars, Grip isn't flying in real time, but he is capturing flight data, such as rotor speed, altitude, the performance of the cyclic and collective, and all data captured by Ingenuity's camera. NASA plans to send additional rotorcraft to Mars, but until then, Grip is the first extraterrestrial, REALLY remote pilot. —P.K.



Ingenuity is designed to avoid obstacles that can spell disaster, like large rocks, when locating a place to land.

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fibers placed 45 degrees to the blades' chords. The breakthrough design results in a stiffer blade that resists twisting. Additionally, a 16-degree twist built into the blades allows for easier hovering.

Ingenuity's swashplate is the same as that of a conventional helicopter. The cyclic and collective controls are sealed against dust and moved by servos that receive commands from the aircraft's computer. The whole shaft is driven by a brushless DC motor in which a ring of magnets revolves around fixed coils, just the opposite of how a standard electric motor runs. "The arrangement gives Ingenuity's motor higher torque and greater power with less draw on the battery," Pipenberg explains.

A six-cell lithium-ion battery powers the helicopter, and about 60% of the electricity is used to keep certain parts of the aircraft warm. A solar panel on top of Ingenuity keeps the battery charged. Some components, such as the servos, can be warmed on command depending on the expected weather, while the avionics box is automatically kept warm at night.

And it all worked better than expected. "Our helicopter is even more robust than we had hoped," says Joshua Ravich, Ingenuity's mechanical engineering lead at NASA's Jet Propulsion Laboratory (JPL). "The power system we fretted over for years is providing more than enough energy to keep our heaters going at night and to fly during the day."

Like a hand fitting the right glove, everything about Ingenuity centered on building the aircraft to fit into the underside of the Perseverance rover. "It's very tight, and we had to be sure it wouldn't interfere with the rover's mission," Pipenberg notes. The landing gear folds up, and a special deployment system developed by Lockheed Martin gently unfolds Ingenuity until it stands upright on the Martian soil. Deployment takes six days.

Anything but Conventional

Temperatures on Mars presented a special challenge to maintaining the helicopter. The planet can get brutally cold at night, with temperatures easily plunging to -130°F, making conventional oils useless. "They would just solidify," says Pipenberg.

Then there's the mostly carbon dioxide atmosphere. While CO_2 won't affect aircraft performance, it does change the performance of lubricants, which are crucial to unheated components, such as the landing gear's leg joints.

"Oxidation is slow, water vapor is low, so lubricants act differently [on Mars]," Pipenberg says. "Graphite [a dry lubricant] becomes extremely abrasive. Other dry lubricants such as molybdenum disulfide work really well on Mars."

Ingenuity's frame, along with its booms, yokes, trusses, and fittings, uses the latest unconventional materials to meet the high bar of space travel. "Advanced composites are absolutely required to do a mission like this," Pipenberg says.

These exotic and continually evolving materials are mostly carbon fibers packing up to three times the strength and stiffness of steel and held together with a variety of specially designed resins and tapes. They're rigid as well as inert, meaning they don't secrete even the most minuscule chemicals or gases, which are emitted more readily in a vacuumlike space.

"Outgassing clouds camera lenses, creates corrosion, and clogs sensors," says Sean Johnson, thermoset product manager at Toray Advanced Composites, which provided advanced composites for Ingenuity. Astroquartz is another unusual material and is used on the rover. "These are fibers that are woven into a fabric to cover and protect antennas with minimal signal interference," he adds.

A variety of layered composite tapes is used to reinforce and strengthen the blades. "You can have a surface that's very thin but with a large number of plies to reduce stress," says Johnson.

Materials used to build the helicopter, Johnson adds, must be able to withstand extreme vibration and extreme temperatures and resist contamination, radiation, and microcracking. The constant cycle of extreme heat and cold in space can cause some materials to suffer very fine cracks that can lead to structural failure.

Materials from Toray Advanced Composites have been used in every Mars rover. "We have a nearly 30-year history in space programs," Johnson says. "Our products have even left the solar system on [NASA's] New Horizons spacecraft [launched in 2006, primarily to study Pluto]."

Ingenuity not only has set new benchmarks in rotorcraft aviation; it's pushed the envelope in space-vehicle manufacturing, as well. "There's an aversion to taking risks in manufacturing, especially in aerospace," Pipenberg points out. "NASA allowed for this to be a high-risk program. We needed to figure out what we didn't know. Ingenuity is really an appropriate name."

The AeroVironment team also traded convention for increased efficiency. "We had our engineers building the hardware, [eliminating] a layer of manufacturing," says Pipenberg. "This allowed us to move quickly, reduce errors, and improve communication."

There's an upside to high-risk missions like Ingenuity that rely on "space-qualified" off-the-shelf components, parts that have already met certain standards and have a proven performance record. Using those materials saves time and money and minimizes loss in case the mission fails, explains JPL's Ravich.

"This avoids all the testing you need for a part to be space qualified," Ravich says. "The screening is already done." Ravich says almost everything except Ingenuity's framework and structural connections are off the shelf.

A few distributors for the Ingenuity project are household names; others are better known in aerospace circles. Among the major components and vendors: battery, Sony Group; radio, LS Research; servos, Maxon; inclinometer, Murata Manufacturing; inertia measurement units (accelerometers and gyroscopes), Bosch; navigation processor, Qualcomm; cameras, Sunny Optical Technology; and altimeter, Garmin.

"The off-the-shelf components for our guidance and navigation systems are doing great, as is our rotor system," Ravich adds. "You name it, and it's doing just fine or better."

Taking commands from the rover on the ground, Ingenuity lifts off amid a barren red vista in this artist's depiction.

NASA/JPL-CALTECH IMAGE

parallels to the Wright brothers' first flight, in 1903.

"We've been thinking for so long about having our Wright brothers moment on Mars, and here it is," says Aung. "We'll celebrate our success and then take a cue from Orville and Wilbur regarding what to do next. History shows they got back to work, and so will we."

To immortalize that moment when the first successful powered flight occurred, NASA removed a small piece of fabric from the wing of the Wright Flyer and glued it to Ingenuity's solar panel before its trip to Mars. In another fitting tribute, the agency officially named the spot on Mars where the helicopter lifted off Wright Brothers Field. The 33-by-33-ft. plot is now recognized by the International Civil Aviation Organization.

Ingenuity Is Just the Beginning

As Ingenuity performs more-ambitious flights on Mars, its success represents just the first step in exploring the planet by helicopter. NASA is planning a second generation of larger, more capable rotorcraft down the road that will lead the way in further space exploration.

The agency will use nontraditional blades (for greater tip speeds), advanced batteries, and more-powerful motors. Eventually, the most advanced class of helicopters may exceed 50 lb., according to engineers at JPL.

These rotorcraft will operate independently from a rover and will likely have their own ground stations. Utilizing the inherent advantages of flight, they'll cover more ground and explore areas rovers can't reach, fetching rock, soil, and ice samples for study. Three more helicopters are on the drawing board, two of them coaxial and the third a hexacopter—which, as its name implies, sports six rotors—to mostly support rovers and landers, according to the NASA report "An Advanced Mars Helicopter Design."

The next helicopter will weigh 10 lb. and have the same blade diameter as the 4-lb. Ingenuity. After that, NASA will take an even bigger leap, with a 44 pounder sporting a 5½-ft. blade diameter. A hexacopter, also weighing 44 lb., will finally fly on Mars. Each of its blades will measure 3 ft. long. Unlike Ingenuity, which has no payload capacity, the advanced helicopters are expected to have payloads of at least 3 lb. each.

After Mars, NASA is scheduled to send Dragonfly, a 10-ft., 990-lb., nuclear-powered rotorcraft the size of a car, to Saturn's largest moon, Titan. The launch is scheduled for 2027, and it will take about nine years for the aircraft to reach Titan, which has an atmosphere four times thicker than Earth's.

Whereas Ingenuity had to be designed with care in order to fly in the thin Martian atmosphere, Titan's dense atmosphere and low gravity will make for easier flying than on Mars. Titan's diameter is 3,200 miles compared with the Earth's moon, at 2,100 miles.

"It's remarkable to think of this rotorcraft flying miles and miles across the organic sand dunes of Saturn's largest moon," said Thomas Zurbuchen, NASA's associate administrator for the agency's Science Mission Directorate, in a statement. "Dragonfly will visit a world filled with a wide variety of organic compounds, which are the building blocks of life."