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SPECIAL COLLABORATION ISSUE

JPL AND AEROVIRONMENT *on* MARS

SUCCEED AT SMART COLLABORATION

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INSIDE THE INGENUITY HELICOPTER:

Teamwork on Mars

The Mars Helicopter Project, a.k.a. Ingenuity, lifts off from the Martian surface, near the Perseverance rover.

April 19th saw what some have christened "a second Wright Brothers moment"—namely, the successful first powered controlled flight by an aircraft on another world. Reaching Mars on the underside of the Perseverance rover, the tiny, autonomous Mars Ingenuity Helicopter (5.4" x 7.7" x 6.4") spun its 4-foot rotors and hovered 10 feet off the ground for 30 seconds. By its third flight, a few days later, Ingenuity would rise 16 feet (5 meters) up, and fly 164 feet (50 meters) at a top speed of 6.6 ft/sec (2 m/sec). Back in 1903, the Wright Brothers logged 120 feet to complete the first controlled heavier-than-air powered flight. Now, squaring that circle, Ingenuity carries a piece of fabric from the Wright Flyer's wing, and its flight site is called Wright Brothers Field.

Six weeks and six flights into its mission as we write, Ingenuity has demonstrated the ability to fly on a planet more than 170 million miles from earth in an atmosphere 1% as thick as ours. The near-miniature vehicle has proved to be an intrepid explorer even as it's survived a computer anomaly on its most recent mission. Talk about punching above your weight.

"Now that Ingenuity is actually flying at Mars, we can begin to assess how things stack up against expectations," noted Håvard Grip, Mars helicopter chief pilot for NASA's Jet Propulsion Laboratory (JPL).

Ingenuity represents the years-long collaboration between NASA/JPL, major unmanned systems manufacturer AeroVironment and a bevy of other companies. The articles that follow chronicle how JPL created the craft's unique navigation system and how AeroVironment's engineering team stepped up in the electrical, mechanical, systems and vehicle flight control areas.

"Working with JPL, I think we've learned a lot," AeroVironment engineering lead Ben Pipenberg said. "It's a very AV project, it's this weird, first-of-its-kind vehicle, but JPL is the best at what they do by far, in terms of space robotics, planetary robotics, and there was a huge amount we were able to learn from them that we'll be able to pull into a lot of our work in the future. It was really good teaming.

"There's a huge amount of pride, a lot of excitement, that it's flying on Mars." ■

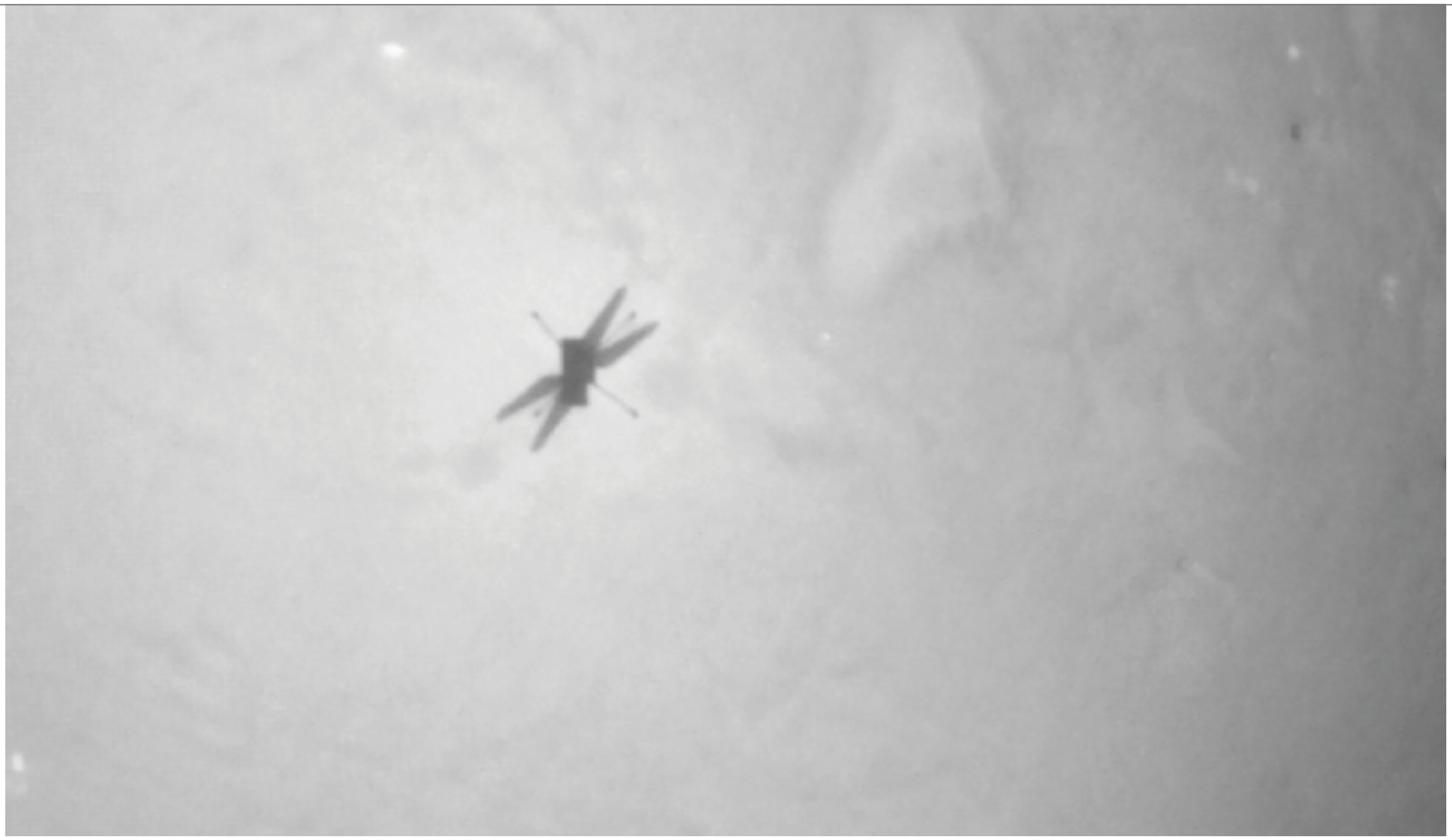
Photo courtesy of NASA/JPL.

JPL: Autonomously Alone on the Red Planet

When Ingenuity, the little helicopter that could, sprang from the Martian surface into the wispy thin Martian atmosphere, it knocked down all kinds of firsts. The first powered, controlled flight on another planet. The first autonomous flight. The first use of an inertial navigation system and visual odometry across an alien world.

by Alan Cameron, PNT Editor

> “Now that Ingenuity is actually flying at Mars, we can begin to assess how things stack up against expectations.”
>
> **Håvard Grip,** Mars helicopter chief pilot, JPL



(TOP RIGHT) The Ingenuity Mars Helicopter’s navigation camera captures the helicopter’s shadow on the surface of Jezero Crater during the rotorcraft’s second experimental test flight on April 22.

To make this happen, NASA invested $85 million to build Ingenuity, accommodate it onboard Perseverance for the long interplanetary flight and parachute deployment, and operate it once it reached distant Mars.

There’s plenty to marvel at in this undertaking, which took the fertile minds of NASA’s Jet Propulsion Laboratory (JPL), NASA Ames Research Center, NASA Langley Research Center and companies that included AeroVironment, Inc. (see accompanying feature) on a six-year journey from inspiration to realization. Awe will be confined within this article to the phenomenon of Ingenuity’s navigation system.

NAVIGATING THE SUBSYSTEMS

The Mars copter’s flight control system consists of four main subsystems: the Mode Commander, setting the overall mode for the flight control system; the Guidance subsystem, providing reference trajectories for the flight path; the Navigation subsystem, giving estimates of the vehicle state; and the Control subsystem, commanding the actuators based on the reference trajectories and the vehicle state.

The specific challenges for the navigation system onboard the UAV include:

- A lack of global navigation aids, such as GPS or a strong magnetic field.
- A large communication time lag between Earth and Mars, preventing real-time communication during flight.
- A harsh radiation environment that can adversely affect computing elements.

Because of the time-lag challenge, Ingenuity has to perform on its own. Autonomously, in other words. Radio signals from NASA Command take 15 minutes and 27 seconds to travel the 173 million miles (278.4 million kilometers) to Mars. Once on the surface, the more well-endowed Perseverance rover served as a communications relay link so the helicopter and Mission Team on Earth could communicate. It passed flight instructions from NASA’s Jet Propulsion Laboratory in Pasadena, California, to Ingenuity. From a Martian hillock 65 meters away, the four-wheeled rover observed and recorded its four-bladed offspring’s history-making flights.

While hovering on its four initial flights, the helicopter’s navigation camera and laser altimeter fed information into the navigation computer to ensure Ingenuity remained not only level, but within the borders of its 10x10 meter airfield—a patch of extraterrestrial real estate chosen for its flatness and lack of obstructions. Because landing hazard avoidance was not prioritized for this technology demonstration, each of those four initial flights began and ended within an area that had been pre-inspected and determined to be safe in terms of obstacles and ground slope.

Ingenuity conducted five flights according to its programmed lifeline across a period of 31 Earth days, or 30 sols on Mars. Then came the surprise ending-to-date, but more on that later.

For the helicopter’s pre-arranged autonomous test flights, under the NASA rubric of “technology demonstration,” it took off, climbed, hovered, translated between a set of waypoints, then descended to land again **(see Figure 1).** Although the helicopter did operate independently during flight, the waypoints were specified from Earth prior to flight.

AUTONOMY?

This, however, raises an interesting and somewhat subtle point: is Ingenuity truly autonomous?

It depends on your definition. Engineers at AeroVironment, which constructed major elements of the helicopter but was not involved in the guidance, navigation and control (GNC) system design, weighed in on the issue.

“It certainly is making autonomous decisions [in managing rotor speed and pitch] to get more cyclic to overcome a wind gust,” said Jeremy Tyler, senior aeromechanical engineer. “It’s managing its altitude, it’s managing its position, all by itself without any external intervention.”

“It’s inherently unstable,” added Matt Keennon, technical lead for rotor system development. “It can’t fly for a half-second without making decisions based on the inertial measurement unit [IMU] and driving the control system.”

“There’s no [navigation] decisions being made onboard,” countered Ben Pipenberg, AeroVironment’s engineering lead on the Ingenuity project. “When Perseverance landed, it used terrain-relative navigation, and it was making decisions based on outside observable data that it was collecting without human input. That would be an autonomous system. Ingenuity is not doing that. It’s essentially using VIO—visual-inertial odometry—just to navigate over the ground in a pre-determined flight path, uploaded from Earth.”

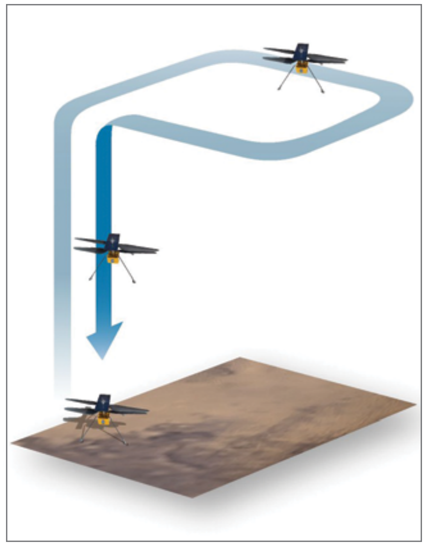


FIGURE 1 Illustration of a Mars Helicopter flight, beginning and ending in the same pre-inspected safe area.

Tyler concurred, after a fashion. “It’s doing its own simple autonomy. But certainly no sophisticated mission planning or decision-making.”

THE NAVIGATION SYSTEM

Engineers at JPL under the direction of Håvard Grip, Mars helicopter chief pilot, developed and assembled the visual-inertial navigation system emphasizing robustness, but with a correspondingly

> “As we continue with our flights on Mars, we will keep digging deeper into the data…”
>
> **Håvard Grip,** Mars helicopter chief pilot, JPL

Photos and figures courtesy of NASA/JPL-Caltech.

limited position accuracy and ability to navigate in complex terrain. In particular, the system assumes that features observed by the navigation camera lie on an approximate ground plane with known slope. This is why the landing field was chosen and why the first four flights did not venture beyond its bounds. The flights took place over relatively flat terrain, with short-term height variations on the order of 10% of the flight height.

The navigation sensors Ingenuity carries are:

- Bosch Sensortech BMI160 IMU, for measuring 3-axis accelerations at 1600 Hz and angular rates at 3200 Hz.
- Garmin Lidar-Lite-V3 laser rangefinder (LRF), for measuring distance to the ground at 50 Hz.
- Downward-looking 640 x 480 grayscale camera with an Omnivision OV7251 global-shutter sensor, providing images at 30 Hz.
- MuRata SCA100T-D02 inclinometer, for measuring roll and pitch attitude prior to flight.

All are commercial off-the-shelf (COTS) miniature sensors, largely developed for the cell phone and lightweight drone markets.

Ingenuity also carried a second camera, a 13-megapixel color camera with horizon-facing view for terrain images, not used for navigation.

Figure 2 shows Ingenuity's avionics system architecture. A radiation-tolerant field-programmable gate array (FPGA) function routes sensor data and traffic between other computing elements and performs low-level actuator control. Most of the flight control software is hosted on the flight computer (FC).

A separate navigation computer (NC), a 2.26 GHz quad-core Qualcomm Snapdragon 801 processor, provides the throughput for vision-based navigation. On the NC, one core is devoted to camera-image processing and another to the navigation filter, while the remaining cores are used for other activity.

The visual-inertial navigation system provides the control system with real-time estimates of the vehicle state: position, velocity, attitude and angular rates. The state estimate is based on fusing information from the onboard IMU, inclinometer, LRF and navigation camera.

HEAD TO THE CHOPPER

"Before each of Ingenuity's test flights," Grip told *Inside Unmanned Systems*, "we uploaded instructions describing precisely what the flight should look like. But when it came time to fly, the helicopter was on its own and relied on a set of flight-control algorithms that we developed here on Earth, before Ingenuity was even launched to Mars."

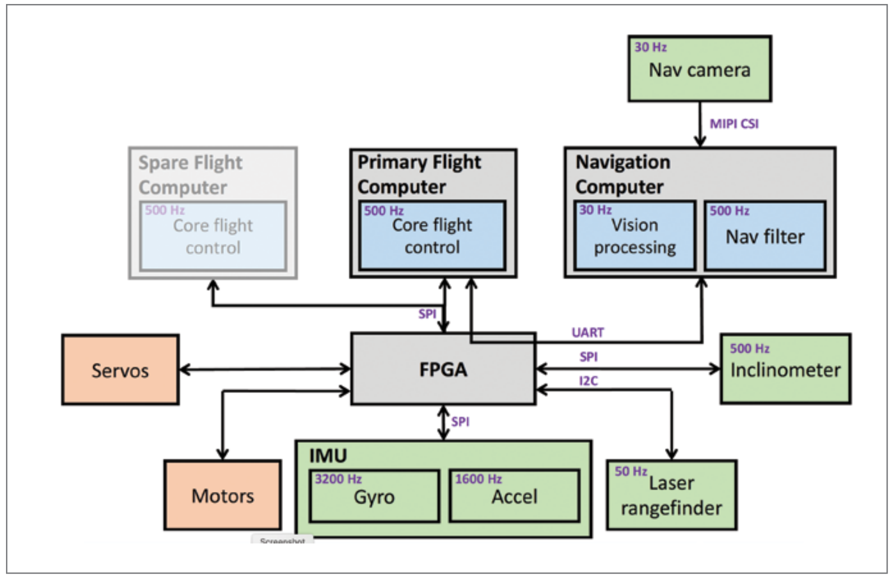


FIGURE 2 The Mars Helicopter avionics architecture.

When the copter rests on the ground, preparing to take off, the inclinometer estimates initial roll and pitch attitude. Based on this, initial estimates of the accelerometer and gyro biases are also obtained.

Once the vehicle is in motion, integration of the IMU measurements is used to estimate changes in position, velocity and attitude. Only the IMU is used for this critical second, measuring acceleration and angular rates. After the helicopter reaches 1 meter off the ground, the laser rangefinder and downward-looking camera are added to the navigation solution. This precaution springs from pre-mission concern that the LRF and camera might be obscured by dust kicked up by the copter blades. The IMU will not output great accuracy in the long-run, but because Ingenuity takes only a couple of seconds to reach 1 meter, "we can make it work," Grip said. Ingenuity then starts using its full suite of sensors.

During hover flight, Ingenuity on its semi-autonomous own attempts to maintain a constant altitude, heading and position. The JPL team has to rely on the copter's estimates on how well it performs this task, as there is limited to no basis for ground truth. But the available data shows that Ingenuity holds its altitude extremely well in hover, to within approximately 1 centimeter, and its heading to within less than 1.5 degrees. Horizontal position can vary up to approximately 25 centimeters, which the team attributes to wind gusts on the Red Planet.

CRUISE CONTROL

Because of the relatively low accuracy of MEMS-based IMUs, navigation aids must bound the growth in navigation errors as the copter cruises. The LRF provides range measurements between the vehicle and the terrain below, giving vertical velocity and position. With the aid of the MaVeN feature-tracking algorithm, the navigation camera tracks visual features on the ground, under the assumption that all features are located on a ground plane with a known slope. This provides horizontal velocity as well as roll and pitch attitude, and helps limit the drift in horizontal position and yaw angle.

However, the latter two measurements have no absolute reference, and their estimates are subject to long-term drift. Therefore, shortly before touchdown at the end of each flight, a navigation camera image is stored for later transmission on Earth, so that an absolute position and heading fix can be obtained by comparison to the known terrain.

"To develop the flight control algorithms," Grip wrote in a NASA blog post updating Ingenuity's fans, "we performed detailed modeling and computer simulation in order to understand how a helicopter would behave in a Martian environment. We followed that up with testing in a massive 25-meter-tall, 7.5-meter-diameter vacuum chamber here at JPL, where we replicate the Martian atmosphere. But in all of that work, we could only approximate certain aspects of the environment. Now that Ingenuity is actually flying at Mars, we can begin to assess how things stack up against expectations."

The MAVeN navigation algorithm used "has no absolute references to any landmarks," according to Grip. "It always operates against a base frame where it sees a bunch of features and tracks them over a limited set of search frames. When it's done, it requires a completely new base frame. It is always tracking in a relative sense, never tied back to a global frame.

MAVeN is implemented as an Extended Kalman Filter (EKF) that also uses the difference between the predicted and measured LRF range. MAVeN has a state vector with seven components: position, velocity, attitude, IMU accelerometer bias, IMU gyro bias, base image position and base image attitude, for a total of 21 scalar components.

MAVeN only tracks features between the current search image and the base image. Because the base frame is frequently reset as features are lost, MAVeN is effectively a long-baseline visual odometry algorithm: the relative position and attitude between the two images are measured, but not the absolute position and attitude. Absolute position and attitude error, in this case horizontal position and yaw, grow over time. The LRF provides vertical position, which bounds vertical position error. In addition, the visual features and flat-plane assumption provide observability of absolute pitch and roll when the vehicle is moving.

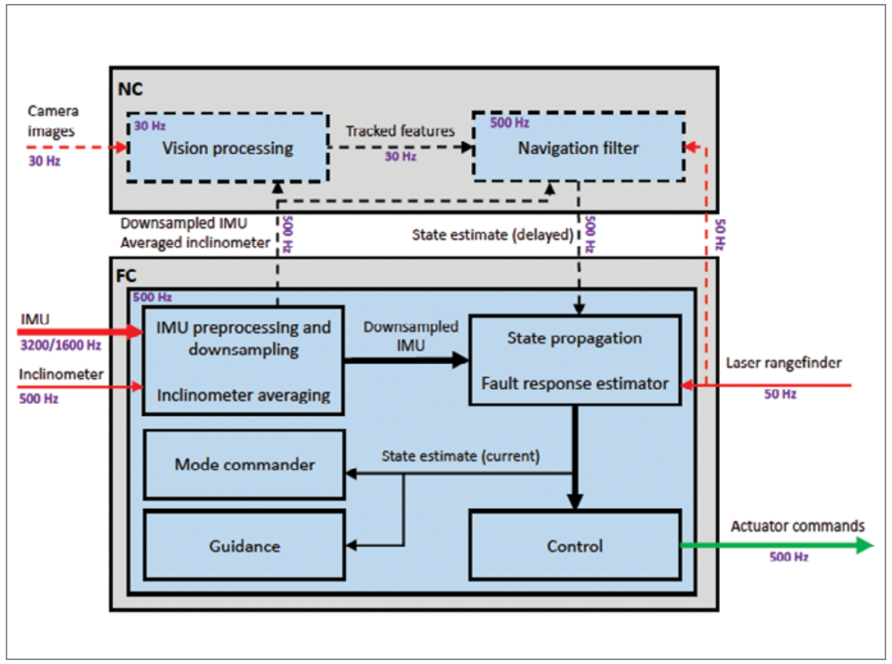


FIGURE 3 Illustration of the flight control software implementation on the flight avionics, with the flow of sensor, actuator and state estimate information. Non-real-time components are indicated with dashed lines.

A key advantage of MAVeN over other simultaneous localization and mapping (SLAM) algorithms is that the state only needs to be augmented with six scalar elements—three for position and three for attitude. The LRF and an assumed ground plane enable MAVeN to estimate 3D position and velocity without introducing a scale ambiguity.

The two main disadvantages of MAVeN are sensitivity to rough terrain, due to the ground-plane assumption, and long-term drift in position and heading. For Ingenuity's technology demonstration phase, this is an acceptable tradeoff, because accuracy degradation is graceful and the algorithm has proven to be highly robust in both simulation and experiments.

Feature detection in base images is performed with an implementation of the FAST algorithm [30], which selects corner-like features that have sufficient contrast between a center pixel and a contiguous arc surrounding the center pixel. An algorithm estimates the displacement of a template from one image to the next, using a gradient-based search algorithm that minimizes the difference in pixel intensity **(see Figure 3).**

BRINGING IT ALL BACK HOME

Landing is an altogether delicate matter.

A rapid sequence of events takes place as Ingenuity descends toward the ground. "First, a steady descent rate of 1 meter per second is established," Grip wrote. "Once the vehicle estimates that the legs are within 1 meter of the ground, the algorithms stop using the navigation camera and altimeter for estimation, relying on the IMU in the same way as on takeoff. As with takeoff, this avoids dust obscuration, but it also serves another purpose: by relying only on the IMU, we expect to have a very smooth and continuous estimate of our vertical velocity, which is important in order to avoid detecting touchdown prematurely.

"About half a second after the switch to IMU-only, when the legs are estimated to be within 0.5 meters of the ground, the touchdown detection is armed. Ingenuity will now consider touchdown to have occurred as soon as the descent velocity drops by 25 centimeters per second or more. Once Ingenuity meets the ground, that drop in descent velocity happens rapidly. At that point, the flight control system stops trying to control the motion of the helicopter and commands the collective control to the lowest possible blade pitch to produce close to zero thrust. The system then waits 3 seconds to ensure the helicopter has settled on the ground before spinning down the rotors."

The downward-facing camera takes several images on landing, which is factored into the sequence for next takeoff.

SURPRISE ENDING

Ingenuity's planned technological demonstration was to last for five flights. Then, sadly, its pathbreaking life would come to an end, its duty done. Its parent and ride to Mars, the four-wheeled Perseverance rover, would continue for two more years to explore the Jezero Crater, site of a lake 3.9 billion years ago, seeking traces of ancient microbial life. Ingenuity would perch motionless forever upon the Martian landscape, the lonely one.

But wait.

"On the last flight, we actually flew somewhere else," Grip said. "We had scouted that terrain previously with the helicopter.

"In that scouting flight, No. 4, we took images using the high-resolution return-to-Earth color camera. We could see on our target airfield, individual rocks, ripples, features, that we then georeferenced against a low-resolution satellite image, so we knew exactly where those features were in a global frame. When we went back on flight 5, we could use those features to reference ourselves."

Flight No. 5's landing looked great, as good as it could have been. Everything went according to plan.

Then a momentous decision was made in Pasadena, to send Ingenuity further—into an operational demonstration phase, very different, at a lower cadence for helicopter operations. As the Mars Project focuses now on rover Perseverance and the science it delivers, "We're in a background role," Grip said, "doing flights every two to three weeks, to demo operational capability, at higher risk, and focused more on aerial imaging capabilities.

"These flights are stretching Ingenuity's capability in terms of altitude, distance and speed. We've covered our basics, shown that a helicopter can fly on Mars, nicely and confidently. We're now stretching the parameters of those flights with the hardware and software that we have on the helicopter."

The increased speed over ground affects the navigation system and how the features the camera is tracking move through the field of view. Additionally, new flights will break the parameter of flying over relatively flat terrain. "We may fly over less flat terrain, that will challenge the navigation algorithm. How less flat is not factored in an explicit way. We can look at the LRF data after the fact and analyze it, but it's not being used in real time to navigate the copter."

"As we continue with our flights on Mars," Grip concluded, "we will keep digging deeper into the data to understand the various subtleties that may exist and would be useful in the design of future aerial explorers. But what we can already say is: Ingenuity has met or exceeded our flight performance expectations." ■

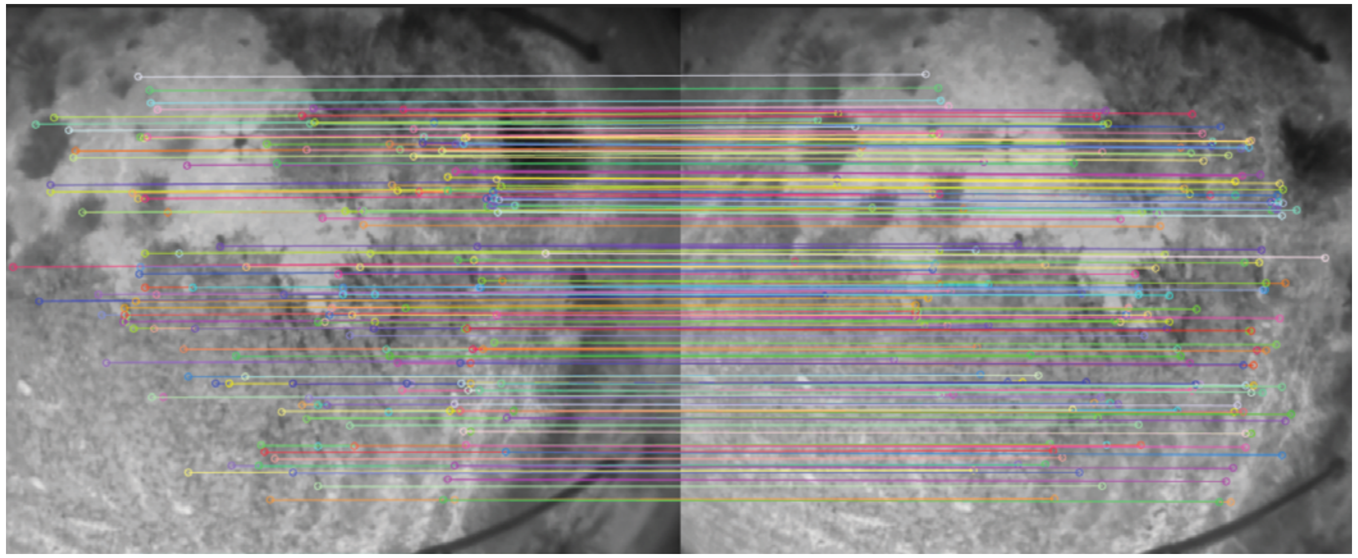


FIGURE 4 Feature tracks between a base image (left) and search image (right) during an outdoor test flight on Earth.

Ingenuity gains operational status as it relocates from Wright Brothers Field.

INSIDE INGENUITY

with AeroVironment

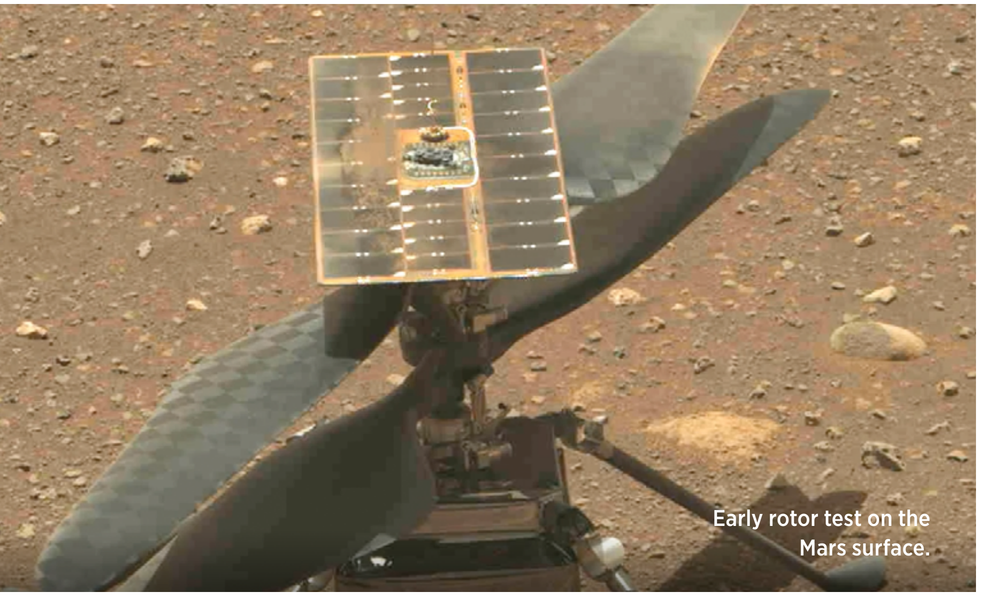
by Abe Peck, Executive Editor
Photo courtesy of NASA/JPL-Caltech.

CONTINUE TO "DESIGNING IT"

AeroVironment's role in fielding Ingenuity is built on a body of work that dates back to its roots exploring human-powered flight, up through miniature products such as the aptly-named Hummingbird and today's HALE (high altitude long endurance) solar vehicles.

For the Mars Helicopter Project, AeroVironment designed and developed the airframe and major subsystems, including its rotor system, rotor blades, and hub and control mechanism hardware. The Simi Valley, California-based company also developed and built high-efficiency, lightweight propulsion motors, power electronics, landing gear, load-bearing structures and thermal enclosures for NASA/JPL's avionics, sensors and software systems.

(The following "oral history" has been edited and reordered for clarity.)



Early rotor test on the Mars surface.

Photo courtesy of NASA/JPL-Caltech/ASU.

DESIGNING IT

BEGINNINGS

MATT KEENNON [AV's technical lead for the rotor system development on Ingenuity and an AeroVironment principal electrical engineer]

AeroVironment started as a company making pedal-powered airplanes, unusual man-carrying airplanes, a Solar Challenger. When I came on board in 1996, we were developing small surveillance aircraft for the military, including a flapping-wing aircraft. We did a lot of DARPA work and DARPA (the Defense Advanced Research Projects Agency) does the really far-out difficult things, not knowing necessarily where it's going to go. The Hummingbird was a basis for our weird and unusual flying machines that seemed to suit problem-solving for unusual application, unusual requirements, really difficult customer requests.

JPL asked us, "How can we demonstrate flight in Mars easily?" and when I came on board, I brought in my ideas from those other projects. We did the subscale, and we also did this other one, which just had a motor and rotor blades. It went up and down on rails, it actually looked like the real helicopter, but it's just basically an empty fuselage. But they all served their purpose of getting the excitement and interest levels raised to the next point of funding.

BEN PIPENBERG [AV's engineering lead on the Mars Ingenuity Helicopter Program and AeroVironment senior aeromechanical engineer; worked on subscale, larger demonstrators and the final build]

Around 2012, 2013, the idea popped back up. The JPL chief engineer for the program came back to AeroVironment and said, "Hey, what do you think about helping out with something like this?" That grew into small-scale risk tests, essentially just putting a rotor system into a vacuum chamber representing a Martian atmosphere, just demonstrating that we can generate lift.

Early on, there was doubt, even within NASA. There isn't data out there that tells you how this is going to work or what isn't going to work. Coming up with tests that are relatively cheap and easy, and allowed to fail—that's pretty important.

OPERATIONAL REQUIREMENTS

PIPENBERG: The big challenge with a helicopter like this is that you're not setting a helicopter on the surface of Mars and then flying it. You're really designing a small standalone spacecraft that also happens to fly. That really defines what a lot of the vehicle requirements are.

The environmental requirements were straight from JPL, from the Mars 2020 mission: the Perseverance rover, mission, launch load requirements. With the launch vehicle—an Atlas V—there's a vibration spectrum we have to survive that defines most of the loads the helicopter is designed against. For controls, there are very specific requirements: natural frequency, rotor blades for hubs, landing gear and all of that flowed down from the JPL-GNC [guidance, navigation, control] team. Sizing constraints was a huge one—what the vehicle is going to have to fit within. And that kind of went both ways, right? AeroVironment saying, "Hey, this is what we need." And Lockheed Martin [its Mars Helicopter Delivery System was designed to transport and deploy Ingenuity] and JPL working to accommodate that, and also us working to change the vehicle design to accommodate the space available. There was a lot of back and forth on a lot of the environment sets.

SURVIVABILITY

PIPENBERG: The first small-scale demonstrators that attempted controlled flight in the chamber [December 2014] were relatively uncontrollable. Those initial small-scale helicopters were essentially built the same way we would build a helicopter that flies here on Earth. The problem we ended up having is that, essentially, in a Martian atmosphere you have these rotors spinning really fast, you have very low aerodynamic forces relative to the inertial forces in the rotor. And so the way the rotor system reacts to control inputs is very different. You also have much lower aerodynamic damping. Think of it like this really high-speed spinning flywheel you're trying to control with very low aerodynamic forces, and there's no damping. So when you see these things flying, they're kind of all over the place, totally uncontrolled. We didn't realize that initially, so after we learned that, then, "OK, where do we need to put a lot more time and effort into the analysis? Where is it really going to be paying off for us?"

That was kind of when JPL took on all of the avionics development, all the guidance, navigation control, all the simulation modeling. For the most part, they handled all the batteries, charging solar array, all that. And AeroVironment took on the airframe, a rotor blade design, propulsion motors, servo swashplates, the primary structure.

KEENNON: Then we went to the full-size demonstrator, the risk reduction, which was really a beautiful piece of engineering. That was the first one that used the full-sized rotor blades. These were all AeroVironment builds; the risk reduction aircraft had the titanium parts that JPL made.

PIPENBERG: In addition to all those [space and Mars] environments, it has to survive a test environment here on Earth. Before we ever get to Mars, we've already gone through almost the entire operational life of the helicopter. Flying on Mars is relatively benign compared to launching on a rocket, in terms of vehicle loads. The hub reaction forces in flight are very small compared to launching on the rocket. That's really the challenge—you're not just designing this to fly on Mars, unfortunately; we're trying to design a very small, lightweight spacecraft that also happens to fly.

ITERATIONS

KEENNON: A dozen concepts on paper were never built. The first one [built] was a box with a motor and rotors, but the first thing that looked like a helicopter. For the subscale, there were two versions that had slightly different layouts, different passive stabilization systems.

Then we went to the full-size aircraft. There was one version we called the risk reduction aircraft. And then we get into where Ben really was taking over the engineering design models.

PIPENBERG: Two engineering development models were intended to be very similar. One was used for flight testing in the JPL 25-foot-wide space simulator. The other was used for environmental testing: thermal vacuum testing, launch loads, putting it on a shaker table and vibrating it, trying to simulate launch, as well as shock testing, radiation and stuff like that. Those two helicopters were functionally similar to the flight vehicle, and what we learned from those helicopters, we would roll into the flight model.

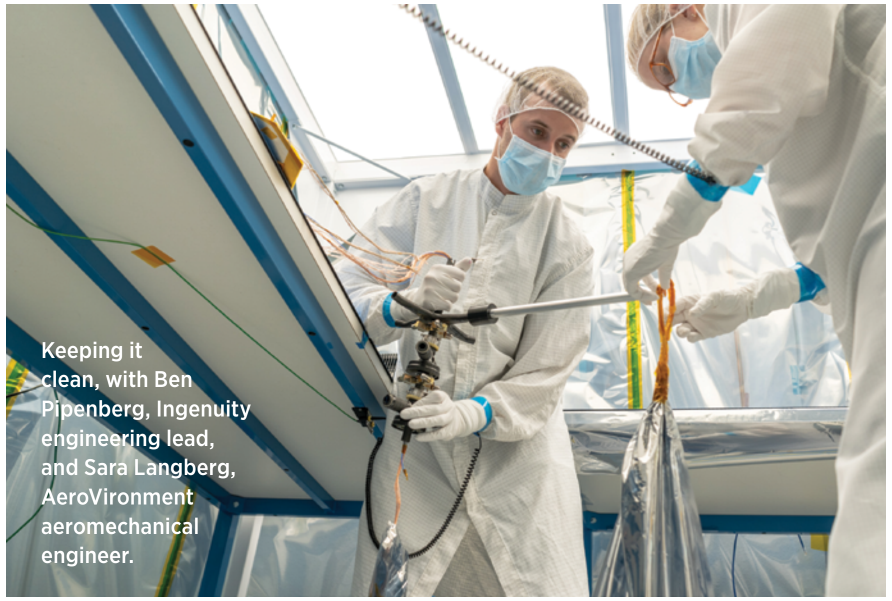
KEENNON: We also built something that looked like a helicopter that was just designed for testing the landing gear, the shock absorbers, the angles. We did all this stuff in a motion capture room; it wasn't a functional helicopter, but it was a functional prototype for testing the landing gear.

PIPENBERG: At the end, it all came together. The airframe, the rotor system, the landing gear, all of that was mated to the avionics, the batteries, the solar array, which was a big team effort. Solera developed the solar cells, we developed the structure they're mounted on and it was mated onto the rover through Lockheed Martin's deployment system. A huge team effort.

That final flight model had everything built to really survive on Mars.

CONTINUE TO "READYING IT"

READYING IT



Keeping it clean, with Ben Pipenberg, Ingenuity engineering lead, and Sara Langberg, AeroVironment aeromechanical engineer.

Photo courtesy of AeroVironment.

JEREMY TYLER: [AV's senior aeromechanical engineer; significant mechanical design work for most of the metal and plastic components: servos, linkages, swashplates, landing gear, hinges, springs, latches]

Thermal expansion was a huge challenge. The operating temperatures on Mars are extremely cold, generally, but they're also very widely varying—it could be negative 100 Celsius, or it could be positive 20 Celsius.

But even that isn't the full range. Every component of the helicopter had to be completely disinfected. For simple things, we could wipe them down or soak them in alcohol. But partially assembled structures that might be damaged by alcohol, we had to bake them in an oven. So we had very

> **“But the big challenge with a helicopter like this**
> is that you’re not setting a helicopter on the surface of Mars and then flying it. You’re really designing a small standalone spacecraft that also happens to fly.”
>
> **Ben Pipenberg,** engineering lead and senior aeromechanical engineer, AeroVironment

high temperatures that the things had to survive, while also being able to withstand the low temperatures of service. It was a unbelievable range of requirements.

Also, a large portion of the Perseverance mission is to look for signs of past life. This is probably the most critical Mars mission so far in terms of biological cleanliness when it arrives. Every component had to be designed to be cleanable; every captured space on every captured component had to be accessible, such that it could be thoroughly disinfected. Even from the mechanical design, we had to figure in disinfecting.

KEENNON: And this is our first space project, so we had to add all this into our plans and our budgets. They came out with their gloves and petri dishes and swabs, inspecting, and taking samples from our work areas. It was intense.

SYSTEMS CHALLENGES

PIPENBERG: A lot of the features you can see on the helicopter were directly a result of GNC requirements. For example, flying in a Martian atmosphere, there’s very low damping; you’re essentially flying a gyroscope. And so, rather than having a huge rotor system like what you would typically have on a helicopter here on Earth, we made a very, very stiff rotor system. And with a counter-rotating, coaxial helicopter like this, your net angular momentum is therefore zero.

Making the rotor system really rigid significantly simplifies how you can control that helicopter. A lot of what you see on the helicopter in terms of even the rotor blade shape, very high taper, relatively thick for how low the Reynolds Number is on these rotor blades—that’s all for structural reasons. That really defines a lot of the reason the helicopter is built the way it is. So, even though we didn’t work on the GNC side, we had to account for that in almost all of the design aspects just to make it controllable. It was a very, very close collaboration between the GNC folks and the mechanical folks.

CHINESE WEIGHTS AND TENNIS RACQUETS

SARA LANGBERG [AV aeromechanical engineer; testing, especially on the blades; mechanical design and fabrication, especially composites. Also swashplate geometry and building load models for the blades and how that interacts with the servos, plus landing gear system in general]

When we’re spinning at such a high RPM, different loads dominate than there would be on Earth. The blades are subject to three loads. There’s the aerodynamic load and an inertial load of the blade through its rotations. But there’s also the propeller moment, which is called “the tennis racquet effect.” It’s the tendency of the blades at an angle to try to flatten themselves as they spin, due to having an off-axis center of gravity like we do.

On Earth, that’s a relatively small issue and doesn’t often need to be accounted for. But because we’re spinning five to 10 times faster on Mars, this effect really dominates. In order to get the servo loads down and into a range where we can get good servo response, we added these counterweights, called “Chinese weights,” to the rotor. If you look at the blades, there’s a hollow carbon fiber cone on each and a tungsten ball in the tip that acts as a counterweight. That counteracts the propeller moment effect, and it doesn’t try to flatten itself quite so much. They’re optimized to reduce the servo loads the most at a hover condition.

KEENNON: The blades are actually twisted, and they’re actually trying to untwist and become flat. So it’s not only grabbing or counterweighting the whole blade, but it’s actually making the blade torsionally stiff enough. That was another driver that fed into the mechanical design of the blades, which again, comes from our high altitude aircraft propeller designs.

We don’t want to add mass to the blade, but we can’t have them untwisting, unfeathering. So, problems upon problems would crop up, and then we would have to solve them in ingenious, lightweight, clever ways. Our background doing these other weird, lightweight, small aircraft, even like the Hummingbird, helped us think about these things in a different way and solve them.

TYLER: On top of all that, the rotor blade is a very highly cambered airfoil, which is quite unusual for a rotorcraft, or at least for a cyclic pitch rotorcraft.

KEENNON: It’s inherently unstable. It can’t fly for a half-second without making decisions based on the IMU and driving the control system. We’ve tried flying this type of helicopter without a control system. It goes bad quickly. It’s just the configuration of a coaxial helicopter.

TYLER: The coaxial router system has no gyroscopic damping whatsoever. Without a digital controller, without a gyro-based autopilot, it’s entirely uncontrollable.

With all those aerodynamic loads of flying and camber and twist, still the inertial loads were dominant. Sara’s analysis, designing those counterweights to ideally balance the inertial loads to the aerodynamic loads, let us really optimize the servo weight, and really minimize the size and power that was needed for those servos to get the bandwidth that was required from the GMC folks at JPL.

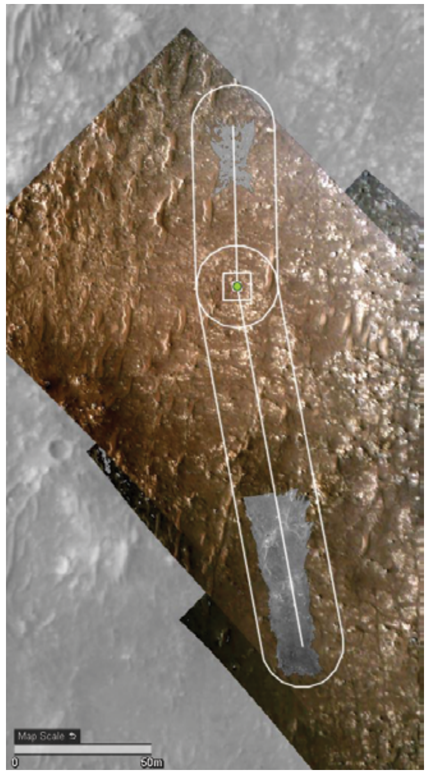
CONTINUE TO “THE MEANING OF IT”

THE MEANING OF IT

On May 7, the Ingenuity Mars Helicopter became an operational scout in addition to its original role as a technology demonstrator. Leaving both Wright Brothers Field and the Perseverance rover behind, Ingenuity flew for 110 seconds, traveling 423 feet at a new height of 33 feet, capturing high resolution color images before landing at its new Red Planet home, which bears the tepid but significant name Airfield B.

PIPENBERG: It’s going to lead to more capable science vehicles on Mars. In general, there are a couple of options. There are much larger helicopters that are being designed kind of as a rover replacement—a big standalone science vehicle that can fly around, has instruments on board. There’s paired concepts with a lander like [2018’s] InSight—you have a smaller helicopter, or a quadrotor, or hexacopter, sort of like Ingenuity-size, that can go fly off and gather samples and bring them back. And then you’ve got scouts for mapping missions, where a small helicopter paired to a rover or a manned mission to Mars, can gather better imagery, or just operational awareness of your surroundings. There’s a lot of different ways to go.

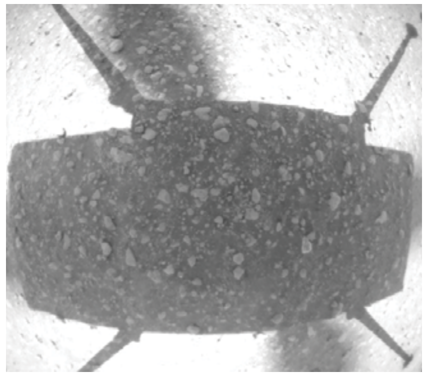
At AeroVironment, we are looking at future technologies that can help: new materials, new fabrication methods, new designs, various types of mechanisms that could be enabling for some of these missions. NASA has published a number of papers as well on kind of the Cadillac science mission; they’re really big standalone helicopters. So there’s a lot of interest, obviously, with a lot of excitement. And I think the big hope here is that that generates really good ideas.



NASA’s Ingenuity Mars Helicopter’s fourth flight path is superimposed here atop terrain imaged by the HiRISE camera aboard the agency’s Mars Reconnaissance Orbiter.

WRIGHT BROTHERS ON MARS?

LANGBERG: I think it’s very much a parallel Wright Brothers moment, in the sense that we’re doing something that no one has ever done for the history of humanity. Way back then, they were doing something everybody thought was impossible. Look at where aviation has taken us now. So I think there’s a lot of parallels into how this is going to open similar doors, but for space exploration.



A picture from the navigation camera aboard Ingenuity captured the helicopter on takeoff during Flight No 2, showing little sign of dust.

KEENNON: This thing is the first combination aircraft and spacecraft, and that is such an insane level of stress put on the designers.

PIPENBERG: It’s a good demonstration of where we’re at in terms of autonomous vehicles, in terms of spacecraft, rockets, deep space communications.

We’re all extremely excited that Ingenuity’s success on Mars has allowed NASA to transition the helicopter from a technology demonstration into an operational demo phase. The increased range and endurance demonstrated in the most recent flights can enable more advanced missions, such as dedicated sensor platforms, mapping applications and sample collection systems.

We’ve had our fingers crossed that we would be able to show that Ingenuity can provide a new dimension to planetary exploration on the surface of Mars, and this next phase will allow us to do just that.

This is really a labor of love. ■

> **“...problems would crop up,**
> and then we would have to solve them in ingenious, lightweight, clever ways.”
>
> **Matt Keennon,** technical lead for rotor system development, AeroVironment

*Photos courtesy of NASA/JPL-Caltech/
University of Arizona and NASA/JPL-Caltech.*

“DARING ENDEAVORS”

AeroVironment’s President/CEO defines the culture, teamwork and execution behind the Mars Ingenuity breakthrough.

Wahid Nawabi, describing the collaborative success of the Mars Ingenuity Helicopter Project.

WAHID
NAWABI
President/CEO, AeroVironment

Wahid Nawabi, the head of multi-domain unmanned systems developer AeroVironment, was buoyant. Engineers and staff from NASA and its Jet Propulsion Laboratory had just visited to debrief in the wake of the Mars Ingenuity Helicopter’s shift from proof of concept to an operational technology craft flying above the surface of its namesake thin-atmosphere world. As a key partner, AeroVironment had developed components from the propulsion system to wiring and landing gear.

“Their words, not mine, that this was the best, the best, collaborative partnership that they could ever even wish for,” Nawabi recounted. “I asked them, ‘Is there anything that we could have done better?’ ‘No, Wahid, there’s nothing. We didn’t even feel like a different team.’ The collaboration was that close, that tight, that important.

> “Everything that we do
> starts and ends with collaboration.”

“The credit goes to our team,” Nawabi said. “I am just a messenger for them.”

Like a proud technological father, Nawabi defined the principles behind his company’s ability to deliver unique, even trail-blazing, solutions. His tentpoles? Collaboration, a culture of innovation and mission-driven execution.

THE ROOT OF SUCCESS

“Everything that we do starts and ends with collaboration,” Nawabi explained emphatically. “When you’re designing a system of systems solution, it is by far one of the most, if not the most, important, attributes of the team and the entire mission.

“You can’t do a project like this without having an incredibly strong collaborative team” Nawabi continued. “Taking things that have never been done before is just what we thrive on. The people we hire, train and develop have an appetite for daring endeavors. That’s No. 1. No. 2, you’ve got to be willing to work passionately as a team. This is not a job. This is what they want to do.”

Nawabi’s description of the helicopter project sounded like a space-age Russian nesting doll. To get to Mars, it had to be specced to fit within the Perseverance rover, which had to fit within the payload bay of the rocket that would carry them from Earth. Tested as an aircraft on our planet, the helicopter functions as a spacecraft on Mars. And the fight control computer, the autopilot, had to be designed in close coordination with JPL.

The stakes around Ingenuity were higher than usual, Nawabi pointed out; after all, it’s harder to fix something that’s 170 million miles away. “You must be able to design systems that 100% cannot fail,” he said. “It’s not like you can launch this thing and go return it and fix it. Every single intricate detail has to be done just perfectly right.

“You’ve got to be able to work in an environment where there’s a tremendous amount of unknowns. This has not been done before, so you have to figure out a way to do it yourself.”

A multi-year project such as Ingenuity requires effective planning. Nawabi endorsed a PDCA model—plan, do, check, act—and ticked off key milestones.

“You develop a theory—what is this concept, and what are we going to achieve at the end of this? You check the concept to make sure it’s valid.”

Next, Nawabi outlined, ‘you develop a set of requirements as a result of that.” For Ingenuity, those requirements included the physics of flight on Mars; size, weight and dimensions compatible with fitting into the rover and the spacecraft; and sufficient autonomy to function far from Earth’s signaling.

“And then,” he continued, “those requirements make it into a project plan that says, ‘Here’s how I’m going to achieve that outcome.’ And then the work starts to be divvied out.

“You test it. And if it works, you develop it more, and you test it again, and you take the learning and you keep improving it.”

MARTIAN MILESTONES

“On Mars, it’s a lot more difficult,” Nawabi noted, citing another set of milestones. “I’ve got a system that works in the lab. Would this system become bulletproof under all these extreme conditions: radiation, shaking, vibration, rattle, extreme temperatures? It will not fail, because it cannot fail—the entire mission’s over.

“What if this thing lands, and it gets hit really hard; let’s test the landing system, make sure it’s robust. The mechanical systems that have to open for this thing to become operational. Powering it up, the solar panels working—do we get enough energy to land and complete the mission? All these things are very, very critical.”

Six flights in, Nawabi turned the proverbial telescope around to peer into the future.

“There already are several concept missions that a flying device on Mars can do much better than a ground robot can do—that by itself is a complete new dimension. For example, samples on Mars in different places have to be meticulously picked up. You can use a rover, but what if the rover failed after taking three samples? You can have an insurance policy with a UAV. You don’t risk a billion-dollar mission with one point of failure. And there are so many other examples. The rover does very, very good things. But it does go slow. And its reach is very limited.”

Nawabi continued: “For every single potential mission in the future, for not only Mars, for any other planetary operations that mankind will take on—we believe it dramatically changes our ability to really progress in exploration and eventually habitating Mars with humans.”

Before concluding, Nawabi mirrored his earlier comment that collaboration bookends all of AeroVironment’s projects.

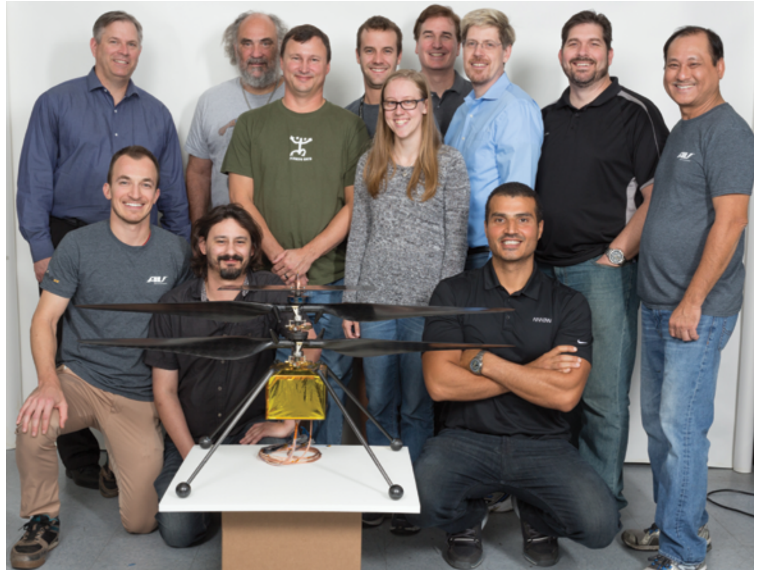
“The most important thing from the beginning,” Nawabi noted, “is that you have a team that is fully committed and believes in the outcome of the mission. You’re going to run into an enormous amount of uncertainty, most likely some setbacks, challenges, questions, problems. You can’t force that belief, it has to come within themselves.

“You take a daring challenge, and a team of very talented people, both at AeroVironment and at JPL—the primary two parties, along with other players—essentially had a moment that has not been repeated since a Kitty Hawk moment 100-plus years ago. Achieving that as a team, across different locations during a pandemic—how could you not be inspired? Just like we look now at how aviation has transformed and changed our lives, and humanity’s lives all over the world, for the last 100 years. The same could be said about this 100-plus years from now.”

One other aspect of collaboration needed to be addressed: how does Nawabi see his role as a leader for such a complex project?

“I am just here as an enabler to remove the barriers, to create the environment and create the atmosphere, so these people can unleash and just basically live up to their potential. We have a thing within AeroVironment that once you know what you have to get done in terms of the mission objective or the customer requirements, get the hell out of the way and let those people run. We let them work as free, collaborative, incredibly talented, incredible minds.”

—Abe Peck



The team behind AeroVironment’s work on the Mars 2020 Helicopter.

Photos courtesy of AeroVironment.