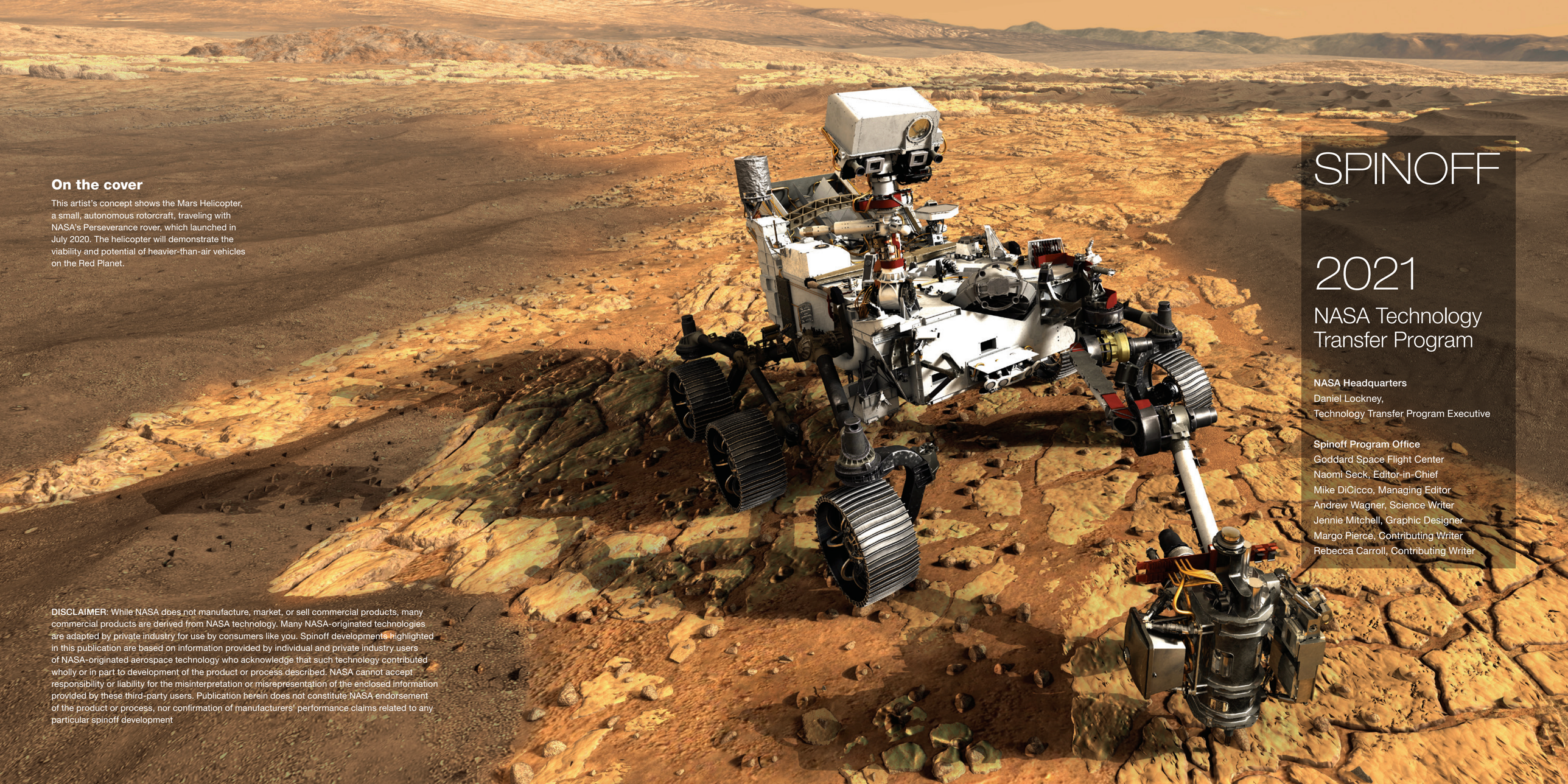
National Aeronautics and Space Administration

SPINOFF

2021



On the cover

This artist's concept shows the Mars Helicopter, a small, autonomous rotorcraft, traveling with NASA's Perseverance rover, which launched in July 2020. The helicopter will demonstrate the viability and potential of heavier-than-air vehicles on the Red Planet.

SPINOFF

2021

NASA Technology Transfer Program

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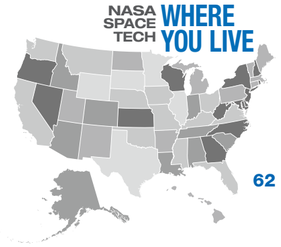


Spinoff (spin´ôf) -noun.

1. A commercialized product incorporating NASA technology or expertise that benefits the public. These include products or processes that:
   - were designed for NASA use, to NASA specifications, and then commercialized;
   - are developed as a result of a NASA-funded agreement or know-how gained during collaboration with NASA;
   - are developed through Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) contracts with NASA;
   - incorporate NASA technology in their manufacturing process;
   - receive significant contributions in design or testing from NASA laboratory personnel or facilities;
   - are successful entrepreneurial endeavors by ex-NASA employees whose technical expertise was developed while employed by the agency;
   - are commercialized as a result of a NASA patent license or waiver;
   - are developed using data or software made available by NASA.
2. NASA's premier annual publication, featuring successfully commercialized NASA technologies.

A SpaceX Falcon 9 rocket carrying the company's Crew Dragon spacecraft is launched on NASA's SpaceX Demo-2 mission to the International Space Station with NASA astronauts Robert Behnken and Douglas Hurley onboard, Saturday, May 30, 2020, at NASA's Kennedy Space Center in Florida. A new era of human spaceflight is set to begin as American astronauts once again launch on an American rocket from American soil to low-Earth orbit for the first time since the conclusion of the Space Shuttle Program in 2011.

Introduction

Jim Reuter
Associate Administrator
Space Technology Mission Directorate
NASA Headquarters

Welcome to the new edition of *Spinoff*! If you've picked up any of our other books in recent years, you'll notice that this one has a whole new look, one of a host of changes designed to improve how we deliver our content to you.

However, the important things remain the same. As ever, we are focused on telling you the wide range of ways your investment in the nation's space agency is paying off for everyone here on the ground, in the form of technological advances and commercial products that safeguard our environment, grow the economy, and even save lives.

So what's new? We're still documenting dozens of spinoff success stories from across the United States, but we've curated 19 of those stories in a quick, easy-to-read section we're calling *Spinoff* Capsules. This year, you can learn about aircraft whose aerodynamics were improved thanks to NASA's most-awarded software, a program to help astronauts visualize repairs that now assists workers on the ground, and NASA expertise that helped improve home tankless water heaters.

We're also going in-depth on some features, introducing the NASA inventor whose lunchtime brainstorm (it involved her drinking straw) led to a product that could finally clean up decades-old pollution and the engineers who copied the biological mechanism geckos use to climb walls to create a gripper for both zero gravity and the factory floor.

Within this section of the book, you will also notice some stories on larger themes. This is a brand-new way to think about our long track record of spinoff successes. With these features, we step away from individual companies and products to look at the broader trends. For example:

- How a single NASA mission, like the Perseverance rover, can lead to benefits across industries and environments, for manufacturing circuit boards, sampling minerals, and even diagnosing infections, (page 24)
- How NASA's support for small businesses has paid off not just in improved space technology but in safer hip replacements, more efficient supercomputer coolers, and even better water bottles, (page 46) and
- How protocols first developed to safeguard the food we were sending to the Moon are now mandated across the food industry here and around the world, drastically reducing the incidence of food-borne illness (page 58).

In addition to these commercial success stories, this issue of *Spinoff* also delves into NASA's response to the coronavirus pandemic and the work our Technology Transfer team did to ensure the innovations our inventors were racing to create or help improve, including new ventilators and sterilizers, got into the hands of businesses and the public for the biggest impact (page 65).

We also feature 20 NASA technologies that the Technology Transfer Program has identified as promising future spinoffs, as well as information on how to license them or partner with us to further develop them for commercialization (page 73).

One last change to highlight: we now publish new *Spinoff* features year-round on our redesigned site, **spinoff.nasa.gov**. Once you've had a chance to read this year's book, we hope you'll visit us there, where you can see our latest stories and browse thousands more in our archives.

Transferring NASA technology beyond the space agency is part of our mandate and our longest-standing mission. *Spinoff* 2021 may look a little different, but the message is not: we're always working to ensure our innovations find the widest benefit, from space to you.

Support teams arrive at the SpaceX Crew Dragon Endeavour spacecraft shortly after it landed with NASA astronauts Robert Behnken and Douglas Hurley onboard in the Gulf of Mexico off the coast of Pensacola, Florida, Sunday, Aug. 2, 2020. The Demo-2 test flight for NASA's Commercial Crew Program was the first to deliver astronauts to the International Space Station and return them safely to Earth onboard a commercially built and operated spacecraft. Behnken and Hurley returned after spending 64 days in space. *Credit: NASA/Bill Ingalls*

SPINOFF Capsules

Over the past six-plus decades, NASA has continually expanded the frontiers of human knowledge, helping us uncover many of the mysteries of the universe. But the work has never stopped there. Here's a quick glance at a variety of examples of technology we built or funded that have been adapted to benefit all of us.

TetrUSS Stacks Up Building Blocks for Aircraft Design

NASA's most popular and most-awarded software simulates aerodynamics for aircraft development and much more

Lockheed Martin has used the Tetrahedral Unstructured Software System (TetrUSS) to make modifications and identify parts most prone to wear on many of its flagship planes, such as the C-5 Galaxy. *Credit: U.S. Air Force/TSgt. Bill Thompson*

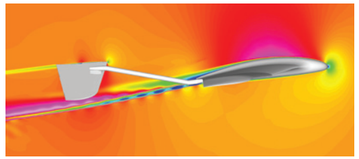
Anyone who excelled at the Game Boy's top-selling video game will recall the animated rocket liftoffs that celebrated high scores. In addition to simulated rocketry and the name, NASA's TetrUSS code has one other commonality with Tetris: unrivaled popularity. The program is NASA's most-downloaded software. It helps design aircraft and spacecraft, but it's also been used to make cars, trucks, and buildings, to model bird flight, and even to investigate plane crashes.

Since NASA's early days, the agency has led the way in software for computational fluid dynamics (CFD), which models aerodynamic forces and flight performance.

TetrUSS, short for Tetrahedral Unstructured Software System, started at Langley in the late 1980s but came of age in the '90s. It's a software suite comprising a flow solver known as USM3D, along with two other codes, GridTool and VGRID, which enable the creation of grids over a model's surface and a lattice of tetrahedrons to represent the air around it.

Unlike other options available in the 1990s, TetrUSS was fast. The program won NASA's Software of the Year award in 1996.

But industry was hesitant at first to trust in CFD. A NASA contract with McDonnell Douglas exploring advanced subsonic airplane designs – and validating them through CFD – helped change that. Rick Hooker, who led the project at McDonnell Douglas, still uses TetrUSS extensively at Helden Aerospace, the company he founded in 2010, based in Acworth, Georgia.



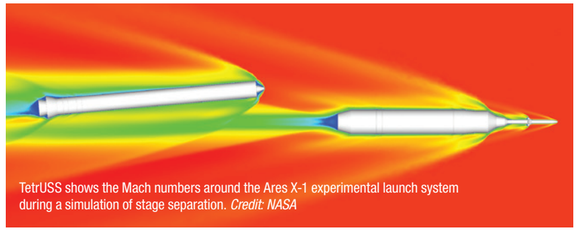
TetrUSS illustrates the Mach numbers around the model of a proposed rocket-powered plane for Mars exploration. *Credit: NASA*

TetrUSS is central to all of Helden Aerospace's work, used in all the company's consulting and forming the basis of its HeldenMesh software suite, which it developed under a couple of Small Business Innovation Research contracts from Langley. For HeldenMesh, the company replaced the VGRID software with its own code to completely automate the grid-generation process, the most labor-intensive part of CFD work. The company estimates the software can build a grid in an hour that would take 60 hours to create manually.

Groups such as the Spaceship Company, Gulfstream, and the Army, as well as NASA, are already using HeldenMesh.

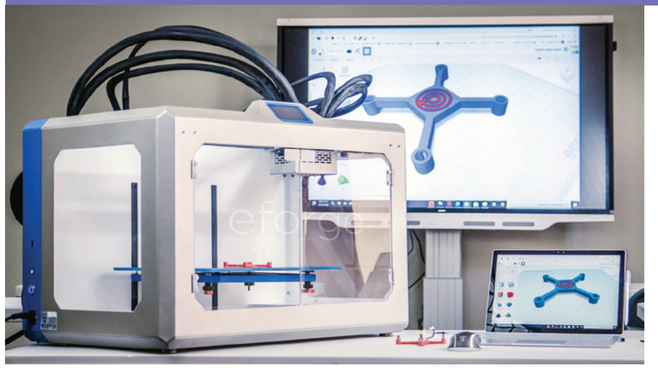
Meanwhile, TetrUSS won its second NASA Software of the Year award, as well as an Apple Design Award, in 2004, after Langley engineers adapted the program for the Mac and Linux operating systems, making it available on consumer-class machines. Distribution went up by two orders of magnitude as academic researchers became major users.

It's now in another major transition period, with a new beta version developed and in testing, which gets more accurate results about 10 to 20 times faster than the existing version. ●



TetrUSS shows the Mach numbers around the Ares X-1 experimental launch system during a simulation of stage separation. *Credit: NASA*

NASA Research Helps Make Electronics on Demand



Electronic Alchemy's eForge 3D printer, developed with NASA funding, can print electronic devices on demand. *Credit: Electronic Alchemy*

The agency's interest in printing components in space results in a commercially available 3D printer for electronic devices and parts

Chance Glenn traces the inspiration for his 3D electronics printer to Star Trek, a TV show with a "replicator" that could produce food, ship parts, and anything else on demand.

With that as his starting point, he developed what eventually became the Electronic Alchemy eForge, a 3D printer that enables anyone to manufacture their own electronics designs on demand. The machine can print sensors, lights, and other electronic components into shapes or onto fabrics or other materials.

NASA has been working on 3D printing technology for years. Being able to print parts or devices in space as needed could help reduce launch mass for long missions by enabling run-down parts to be recycled and replaced. 3D printing could also help crews respond to unexpected situations when there isn't time to return to Earth or wait for a supply ship.

NASA has been studying 3D printing in space for years because of its potential to make spaceflight safer and missions nimbler. Here, astronaut Barry Wilmore holds a ratchet wrench created with a 3D printer aboard the International Space Station in 2014. *Credit: NASA*

With that interest in mind, NASA's Marshall Space Flight Center in Huntsville, Alabama, awarded Glenn's Huntsville-based company about $1 million in Phase I and II Small Business Technology Transfer contracts to continue developing its printer. Electronic Alchemy also received a small Phase III Small Business Innovation Research contract.

Thanks in part to that funding, Glenn and his team developed multiple printable materials with electronic properties and a 3D printer capable of printing different materials without manually changing the printer heads.

The eForge semiconducting materials can be used in switches, communication equipment, and solar cells, or combined to create diodes and transistors for integrated circuits, computers, amplifiers, and more.

Electronic Alchemy is continuing to develop new materials for the printer, Glenn says, including a filament that lights up with an electric current and a piezoelectric material that generates an electric charge in response to mechanical stress. Users will design components within the eForge software or upload files created in other programs.

The first eForge devices became available for presale in October 2019 through a Kickstarter campaign. The printers were expected to ship in late 2020.

Glenn hopes the machine will appeal to maker spaces at universities and schools, as well as in research and development settings. "You can design something, print it, test it, make sure it works, and if it doesn't, you can redesign and reprint it, all within minutes," he said.

NASA was essential to the Electronic Alchemy eForge, he added. "I can safely say that this would not be anywhere near where it is without NASA's input." ●

Answering the Call of Distress

Software created with NASA expertise helps improve search and rescue system established under NASA's lead

As companies and other entities continue making use of NASA know-how, spinoffs from the space agency are bound to bump into each other now and then. That's what happened as the lifesaving Search and Rescue Satellite Aided Tracking (SARSAT) system underwent a major expansion over the last several years.

The U.S. SARSAT system and its global counterpart, COSPAS-SARSAT, detect and locate distress signals from emergency beacons and have enabled the rescue of more than 48,000 people worldwide. In the United States, more than 10,000 people have been saved since the first satellite transponders and ground stations went into effect in 1982.

NASA led the system's creation and remains the research and development lead, and the National Oceanic and Atmospheric Administration (NOAA) manages the ground stations in the United States (*Spinoff* 1982, 2000).

Since going into effect in the early 1980s, the Search and Rescue Satellite Aided Tracking (SARSAT) system and its international counterpart COSPAS-SARSAT have enabled the rescue of more than 48,000 people worldwide, including more than 10,000 in the United States. NASA took the lead in developing the system and remains the U.S. SARSAT research and development lead. *Credit: U.S. Air Force/Senior Airman Sean Sweeney*

Historically, SARSAT transponders have piggybacked on both low-Earth orbiting satellites and much more distant geostationary satellites. The first can calculate a beacon's location, while the second can immediately receive and relay the distress message, but neither can do both well.

Over the last decade, SARSAT repeaters have also been added to many of the world's navigational satellites, which operate in medium-Earth orbit (*Spinoff* 2012). The Search and Rescue Office at NASA's Goddard Space Flight Center in Greenbelt, Maryland, assessed the medium-Earth orbit SARSAT platform and developed and tested the first ground station to monitor these new transponders. This led to a network of such stations that went online in 2018 as part of the system run by NOAA. It uses multiple simultaneous signals to immediately triangulate a beacon's position. This resulted in nearly instantaneous detection and location, in some cases lessening the delay from hours to minutes. NASA and NOAA continue to improve the ground system.

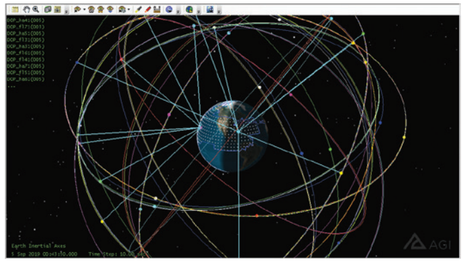
Medium-Earth orbit satellites added to the SARSAT system over the last decade or so have dramatically reduced the time it takes to respond to signals from emergency beacons like this one. *Credit: U.S. Coast Guard*

As the number of these satellites exceed the number of antennas dedicated to them on the ground, the ground network had to make difficult decisions about which satellites to track at any given moment. To solve the problem, NOAA turned to Greenbelt, Maryland-based Orbit Logic Inc., which specializes in software for scheduling and mission planning.

The company's founders built their expertise in the field at NASA: Alex and Ella Herz, the company's president and chief operating officer, respectively, worked on payload engineering and operations as contractors at Johnson Space Center in Houston in the late 1980s and early '90s, when scheduling was a major challenge for space shuttle payloads. The third founder, Orbit Logic Vice President Doug George, later worked with Alex to build the scheduling software for the Vegetation Canopy Lidar satellite at Goddard (a project that was ultimately canceled).

When the three founded Orbit Logic in 2000, they set out to create a planning and scheduling tool flexible enough to be applied to any space, or even non-space, mission. Working with two other companies, including the maker of Systems Tool Kit (STK), they built STK Scheduler (*Spinoff* 2017).

Now STK Scheduler helps SARSAT ground stations choose which medium-Earth orbit satellites to track by weighing priorities against the limited number of antennas to generate a pointing schedule that ensures the highest accuracy for locating distress signals. ●



Orbit Logic's STK Scheduler software, based in part on the company founders' long experience with NASA mission planning, helps a limited number of SARSAT antennas choose which medium-Earth orbit satellites to track at any given time to maximize accuracy for locating distress signals. *Credit: Orbit Logic*

Catch the Waves

Instruments like spectrometers aboard research aircraft like the Stratospheric Observatory for Infrared Astronomy need to be small to fit in confined spaces on the plane. Making capable Faraday rotation isolators is vital to this miniaturization process. *Credit: NASA/Tom Tschida*

NASA-funded sensors test 5G cellular systems

It's very important that the highly tuned components in sensitive instruments, whether on a spacecraft or used in a lab, don't see their own reflection. In sensing devices across the electromagnetic spectrum like radar systems, structural elements called waveguides are used to direct signals between components, but their design can cause reflections. When a signal and its reflection intersect, they produce standing waves which can seriously degrade system performance. Devices called Faraday rotation isolators are used in all kinds of equipment to suppress these standing waves. The Faraday effect, discovered in 1845 by Michael Faraday, states that magnets in a ferrite material can change the polarization of an electromagnetic signal. Isolators use this principle to rotate reflected signals into a resistive layer that absorbs them.

Instruments aboard Earth-observation aircraft and satellites, such as spectrometers, take measurements in wavelengths of a few millimeters or smaller. NASA's Jet Propulsion Laboratory in Southern California needed isolators that worked with these wavelengths to conduct spectrometer experiments. However, existing isolators maxed out slightly above 100 gigahertz – about a three-millimeter wavelength – and caused a high level of signal loss.

Micro Harmonics hand-builds a wide range of Faraday rotation isolators for various applications and wavelengths. *Credit: Micro Harmonics*

Created with the help of SBIR funding, the ferrite cores inside a Micro Harmonics isolator are small enough to be used in both sensors on satellites and instruments on the ground. *Credit: Micro Harmonics*

Under a Small Business Innovation Research (SBIR) contract with JPL, the team at Micro Harmonics in Fincastle, Virginia, developed a hand-built Faraday rotation isolator that could work at much higher frequencies and at higher power levels. They realized the solution was in the materials. Typical isolators use a long, magnetized ferrite core, which is responsible for most of the signal loss. Micro Harmonics shortened this core to its minimum possible length and tuned the magnetic field, significantly reducing the signal loss. The company also replaced the thermally insulating support washers used to suspend the ferrite in the waveguide with a diamond disc, which channels heat away from the resistive layer. They were able to get the low-loss isolators to work at 100 gigahertz, and subsequent developments achieved frequencies in excess of 330 gigahertz.

Now Micro Harmonics is seeing interest from universities and laboratories around the world. Because new high-speed cell phone bandwidths are in the millimeter range, it is important to test how these frequencies behave in several environments. Corporate telecommunications labs testing 5G networks need analyzer equipment outfitted with these extreme isolators to make sure the new systems function properly. Micro Harmonics has already sold their technology to analyzer manufacturers like Keysight.

Micro Harmonics is now on its fourth SBIR contract with NASA, this time working with researchers at Goddard Space Flight Center in Greenbelt, Maryland. While the company's current models can handle the heat, this latest research contract focuses on isolators that work in extremely cold temperatures dealing with electronic component cooling in space, and the company is hopeful that these will have a place on the market as well. ●

Devices to test high-speed cellular networks require specialized isolators to work properly. Several manufacturers of this equipment have contracted with Micro Harmonics to provide isolators for 5G testing. *Credit: Ahmet Cigsar via Getty Images*

Debugging Code Is Rocket Science

A simple NASA static program analyzer finds coding errors for business as well as rockets

Industrial machinery, such as this baler, can be dangerous to operate, so it has strict safety requirements. The Inference Kernel for Open Static (IKOS) Analyzer developed by NASA helps companies find and correct programming errors in controller systems for these machines, ensuring safe operations. *Credit: JE Electronic A/S*

Incorrect computer code can blow up rockets, as NASA learned from the first launch in the European Space Agency's Ariane 5 rocket series. The 501 rocket used computer code written for the Ariane 4 series – but the change to the rocket systems resulted in an anomaly responsible for an explosion 37 seconds after launch. Finding and fixing coding errors, or bugs, required a new approach.

The airline industry, equally concerned about safety, needed a similar tool.

Software errors are even found during deployment, a major concern, explained Guillaume Brat of NASA's Ames Research Center in Silicon Valley, California. Industry lobbied NASA to help with software verification, and IKOS is one of the tools the space agency developed.

The Inference Kernel for Open Static (IKOS) Analyzer can evaluate any program written in C or C++ computer language, without running the program it's analyzing. It looks for mistakes inadvertently introduced by programmers, similarly to how a grammar-check program might find errors in an essay.

The program will occasionally identify some coding as having an anomaly when it doesn't. Fortunately, IKOS has a low rate of those mistakes. Error-free code is marked green. Problems are noted in red. And yellow indicates a potential problem that requires a programmer's review. Less than 5% of the code is mistakenly marked as needing correction, compared to 20 to 50% for other automated analyzers.

The automated review ultimately saves thousands of staff hours and related expenses. The cost of catching and fixing a software error grows exponentially with each phase of the development cycle, adds Brat. Periodic use of a tool like IKOS makes it possible to uncover bugs early – and it only takes a few minutes to review millions of lines of code.

IKOS was "optimized for the type of software found in civilian aircraft, ranging from small drones to transport aircraft," he notes. Helping the airline industry attain software certification required by the Federal Aviation Administration was a key motivator driving the development of IKOS. Mandated code review was time-consuming and expensive.

But now anyone can download the open source program and use it at no cost. Private companies, individuals, and government institutions downloaded IKOS more than 1,200 times since 2013, and it has gathered 1,255 stars on GitHub. The software is improving the quality of computer code used in a variety of applications.

One company that relies on this bug detector is JE Electronic A/S. The Danish company makes controller systems for industrial machines. In addition to using the software to automatically find bugs before they enter the product, the immediate feedback helps new programmers improve their skills while they work, according to Mikkel Johnsen, software engineer at the company.

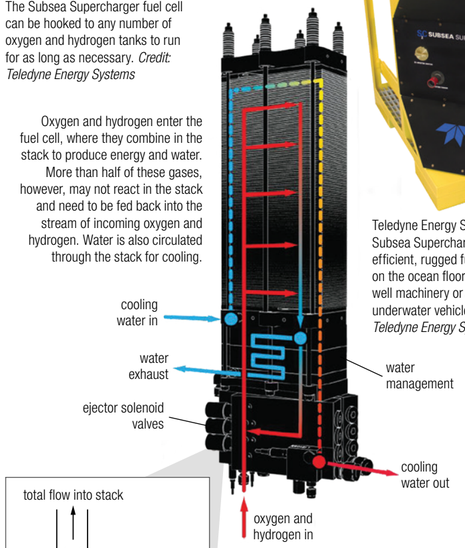
Using IKOS "enables us to keep developing the code base with confidence in the quality," he said. ●

The Atlas V rocket launches NASA's Lunar Reconnaissance Orbiter and Lunar Crater Observation and Sensing Satellite in 2009. Some of the computer code can be used from one generation of rocket to the next. To make sure the introduction of a new rocket system doesn't produce errors, the IKOS Analyzer flags possible bugs for programmers to review and fix. *Credit: NASA*

Space Fuel Cell Provides Deep-Sea Power

The Subsea Supercharger fuel cell can be hooked to any number of oxygen and hydrogen tanks to run for as long as necessary. *Credit: Teledyne Energy Systems*

Teledyne Energy Systems' Subsea Supercharger is an efficient, rugged fuel cell for use on the ocean floor, powering oil well machinery or autonomous underwater vehicles. *Credit: Teledyne Energy Systems*



The fuel cell's ejector nozzle effectively becomes a Venturi pump. As gases coming from the tanks pass through a choke point, they're forced to speed up, which causes their pressure to drop. That's where the line bringing unused reactants back from the stack is connected, and the low pressure draws them in, pulling them back into the stack so they're not wasted. An engineer at Johnson Space Center came up with the idea of replacing a mechanical pump with the nozzle, increasing reliability and efficiency.

Rugged, reliable fuel cells provide power for offshore drilling

"Almost everything you need in space, you also need under the ocean," said Thomas Valdez, manager of chemical engineering at Teledyne Energy Systems in Hunt Valley, Maryland.

Both environments are cold and corrosive, and more importantly, both are difficult to access when repairs, replacements, or refueling are needed. This means they require systems that are rugged, reliable, long-lasting, and efficient.

So after Teledyne Energy Systems worked on fuel cells with NASA, the company is taking the resulting cells first to the offshore oil drilling industry.

In the late 2000s, a team at NASA's Johnson Space Center in Houston was working on a fuel cell for the space shuttle when one engineer came up with an idea to replace the mechanical pump that usually maintains circulation of reactants in a cell with a simple, non-moving part. Where the pump would normally go, Johnson engineer Arturo Vasquez installed an ejector nozzle that passively combined unused hydrogen and oxygen that had already passed through the cell with new hydrogen and oxygen coming in from tanks, using something called the Venturi effect (see diagram at lower left).

Removing the mechanical pump eliminated a common point of failure and a drain on the cell's energy, making it more efficient and reliable. The nozzle also took up less space. The team called it an ejector-driven reactant circulation system.

They demonstrated their invention using a fuel cell from Teledyne Energy Systems, drawing the company's attention, and under a 2012 Space Act Agreement, Teledyne paid NASA to help design, build, and test a fuel cell with the new technology.

In 2018, the company released its first commercial fuel cell featuring NASA's innovation – the Subsea Supercharger.

So far, the technology has received the most interest from well operators, who can use it as a backup to the power lines typically run from the ocean surface. If a well has to shut down due to damaged power lines, the operator can lose upwards of $1 million per day, with shutdowns often lasting weeks. A fuel cell that avoids halting operations quickly pays for itself. And for exploratory wells, the fuel cells can take the place of power lines until a productive site is discovered.

Meanwhile, companies that serve well operators often rely on underwater remotely operated vehicles to inspect and service wells. These run on battery packs that need frequent recharging, especially in cold water. A Subsea Supercharger, which works well in cold water, can act as a charging station for underwater vehicles, providing months' worth of power.

The military is also a customer for charging underwater vehicles, and the Federal Aviation Administration has purchased a fuel cell based on the ejector-driven reactant technology for hybrid-electric aircraft research. ●

Eagle Eyes in Treacherous Skies

A rugged drone designed for NASA supports research and commercial enterprise from the air

Tornados can flip a car when the wind speed reaches 122 mph, making them unpredictability dangerous. Volcanic eruptions are as toxic as they are destructive. Researchers are working hard to improve forecasting techniques and earlier warning systems for these and other extreme events, but they need more data. Collecting that data, though, is no simple task.

Measurements taken from the air at different altitudes add an important perspective. A remotely piloted vehicle equipped with the relevant sensors can dramatically reduce risks for researchers, costs less than chartering a helicopter or plane, and is more eco-friendly than a large aircraft.

But a drone must be rugged to perform effectively under such extreme conditions. Thanks to partnerships between NASA and a company in Boulder, Colorado, called Black Swift Technologies, such a drone exists: a fixed-wing aircraft called the S2.

Now that same drone provides researchers and commercial enterprises, including farmers, surveyors, and the oil and gas industry, with a cutting-edge alternative for gathering reliable aerial data.

The most important result of the company's work with NASA is a fully integrated set of miniaturized instrumentation that delivers usable data under extreme conditions, said Geoff Bland, at NASA's Wallops Flight Facility in Wallops Island, Virginia, who supported multiple Small Business Innovation Research (SBIR) projects with Black Swift to develop the technology, beginning in 2012.

As part of the SBIR work with Goddard and other agency field centers, the company also designed a new airframe with improved electronics. The unique body design houses sensor systems inside the nosecone to help protect them from extreme conditions and also lets users easily swap sensors in the field.

For the Institute of Arctic and Alpine Research at the University of Colorado, the modular, rugged vehicle was perfect for atmospheric sampling in Greenland up to 14,000 feet at minus 20 degrees Fahrenheit.

The pilot interface, called the SwiftCore Flight Management System, is an original program that makes it easy to see and address in-flight activity. Refined and tested during the SBIR sensor research, the simple interface helps the operator to focus on the flight map and data points about the health status of the vehicle.

Bland called NASA's work with Black Swift an "excellent example" of how public/private partnerships are essential for bringing about the technology development for long-term success in aviation. ●

The S2 is a remotely piloted vehicle that uses a modular design for easy sensor replacement in the field. Designed to meet NASA atmospheric measurement needs, the drone, made by Black Swift Technology Inc., is now used by universities for research and by industry for site surveys and more. *Credit: Black Swift Technologies Inc.*

Collecting wind speed and other data in demanding conditions requires a rugged drone. The work Black Swift Technologies did with NASA resulted in the S2, a remotely piloted vehicle that will fly in strong winds, even when the air is filled with debris such as volcanic ash, such as this plume bursting through cloud cover. *Credit: NASA*

Keeping Tabs on the Sky

Pilots depend on air traffic controllers, ground control and other air traffic management professionals to provide up-to-date flight data. Harmony Horizon, a Metron Aviation Inc. flight management software, facilitates the sharing of essential data, such as helping a pilot know where to land, at airports in several foreign countries such as Australia and South Korea. *Credit: michal_staniewski via Getty Images*

Research done for NASA is now helping airports and businesses around the world track airplanes

Think of the national airspace as a complex highway system, but with planes. They're all moving at different speeds and converging on relatively few airports, intent upon arriving safely and on time. Like the highway patrol, the Federal Aviation Administration (FAA) oversees the busy thoroughfares overhead.

Keeping different zones of air and ground activity safe and efficient requires multiple groups. Each one uses a unique software program to support their specific responsibilities.

Over the course of 10 years and multiple NASA Small Business Innovation Research contracts, most of them through Ames Research Center in Silicon Valley, California, Metron Aviation Inc. collaborated with NASA on research and development, which led to a new tool to help all these groups communicate better.

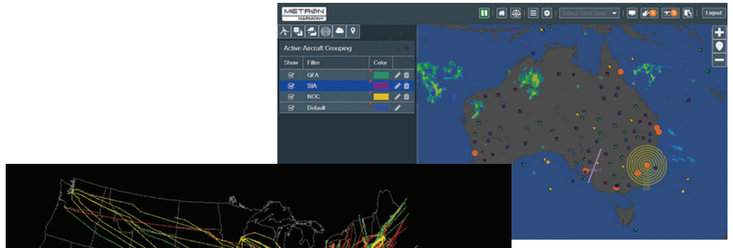
The Herndon, Virginia-based company, a subsidiary of Airbus, has now adapted the software for commercial flight providers as a companion tool to automate the communications they use to share schedule details with the FAA.

Metron's Harmony, a commercial software package, also shares flight data with any airport authority. Proprietary algorithms track flights, predict weather impacts, and propose alternative flight paths. Additional tools keep users up to date with air traffic around the world.

The software's weather translation tool is a "big leap" in air traffic management, according to Bob Hoffman, vice president of research and engineering for Metron. It calculates where and how weather will impact the air traffic system. With that information, Harmony can quickly calculate fuel savings for a new route, the cost of time spent waiting on the ground, and other factors related to rerouting and ground delays.

The scaled-down version of the software, called Harmony Horizon, is used by businesses wishing to keep track of flights and air traffic agencies in other countries. This web-based program provides current air traffic management information that helps the corporations relying on air deliveries stay current with the ever-changing conditions in the airspace. Horizon includes the weather-monitoring feature and other services, but it's not capable of sharing information with the FAA.

Harmony is now being adopted by air traffic agencies around the world. Colombia, Singapore, South Korea, Australia, and South Africa are all using the program to help manage their air traffic. ●



Harmony provides an aircraft situation display to depict airborne aircraft movements on a map so that airlines and businesses can see where planes are at any given time. *Credit: Metron Aviation Inc.*

NASA's Sherlock Air Traffic Management Data Warehouse shows one day of air traffic for Charlotte Douglas International Airport. There can be over 5,000 aircraft sharing U.S. airspace, and software such as Metron Aviation Inc.'s Harmony program makes it possible for air freight and other businesses to quickly share information with all air traffic managers about their flight schedules. *Credit: NASA*

Odor-Eliminating Shoe Inserts Rely on NASA-Tested Cloth

Zorpads patches use a material that NASA has considered for spacecraft filters

Zorpads shoe inserts eliminate odor with an activated carbon cloth NASA has tested for spacecraft filtration. *Credit: Zorpads*

This is the story of a space-age shoe insert that got its start when a graduate student with smelly feet took off her shoes and another tapped into his aerospace experience to solve the problem.

The result was Zorpads, shoe inserts that use an extremely porc carbon cloth to absorb odor. The inserts also work in gym b cans, and other foul-smelling places, the company says.

Activated carbons are used in all crewed spacecraft to condit atmosphere for breathing and for odor control, for example, ir filters, according to Jay Perry, who works on filtration technolog NASA's Marshall Space Flight Center in Huntsville, Alabama.

"There is a rich and long history of using activated carbons for tl applications going back to Project Mercury," Perry said, refe to NASA's first human spaceflight program in the late 1950s early '60s.

In most of its applications, NASA uses granular activated carb but in 2015 the agency ran some tests to see if multiple la of carbon cloths, including the one that Zorpads uses, c filter more effectively. For that particular application, the grar carbon outperformed the cloths. But the cloths were still sh to be extremely absorbent, making them ideal in other situati including as dressing for wounds.

Zorpads have a small "footprint" thanks to the extreme absorption capacity of the activated carbon cloth they are made from, making them suitable for a variety of shoe types. *Credit: Zorpads*

And now feet, too.

Before attending Harvard Business School, where he and four c classmates developed Zorpads as part of an assignment, T Wiegele had worked with activated carbons during stints at the purifying company Brita and at SpaceX, where he consulted wit engineers, including Perry, on spacecraft atmosphere purifica

"I came across a number of really interesting materials, and this one kep staying in my mind," Wiegele said.

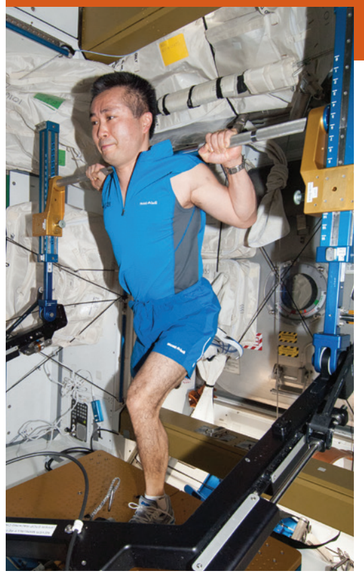
"Later when I started to develop the shoe insert, I realized this was the perfect material for that application," he said. "NASA had done a lot of testing on it, and those results helped us identify it as the right material from the outset."

To the business school study group's surprise, the project won accolades. Wiegele and one of the classmates, Sierra Smith, incorporated the company in New York in 2016 and went on to win a $150,000 investment on Shark Tank, the business reality TV show where entrepreneurs pitch their ideas to investors.

With the help of a material that NASA has also explored for purifying cabin atmosphere in space, Zorpads aims to improve on the odor-eliminating inserts on that are already available and, in Wiegele's words, be "much more effective and better than all the other technologies that are on the market." ●

Fix it Like an Astronaut with Augmented Reality

A program to help astronauts visualize repairs assists workers on the ground



Japanese Aerospace Exploration Agency astronaut Koichi Wakata works out on the Advanced Resistive Exercise Device (ARED) on the space station. Maintenance procedures for the ARED have been digitized to work with the ProX virtual reality guidance technology developed by Tietronix Software Inc. *Credit: NASA*

When astronauts on the International Space Station venture outside to install new equipment or perform maintenance, dozens of people on Earth are involved, helping review, practice, and support the procedure. This kind of labor-intensive field support is something few companies can afford, but NASA technology is making a new kind of on-demand virtual support available on Earth.

For work such as maintenance on HVAC equipment or repairs at a remote monitoring station, a technician typically follows established "best practices." But mistakes or unusual circumstances can slow productivity and cause costly problems.

Astronauts, like field crews, depend on predetermined instructions. And like those field crews, they sometimes encounter situations not addressed in the handbook. Astronauts on Mars, for example, will face days-long communication blackouts when the planet is on the other side of the Sun. NASA has been developing technology to enable astronauts to deal with unexpected situations on their own.

Working with Houston-based Tietronix Software Inc., NASA developed, ProX, a system of procedural guidance using machine learning and artificial intelligence. The step-by-step instructions are presented using augmented reality and 3D animation to help astronauts use and maintain a variety of equipment.

The development took place over a decade under multiple contracts with NASA's Johnson Space Center in Houston. Tietronix has since taken ProX and developed it into Procedure Genius, or ProG, first available in 2016.

ProG provides instructions for any kind of task, and it can monitor activity in real time, catching mistakes when they happen. The system uses sophisticated algorithms to recognize errors, determine how to correct them, and direct the remediation.

The visual display can superimpose text, animation, or both over the equipment for each step. All the while, a visual record confirms the successful execution and completion of the work. At the end of the task, the imagery can be sent back to the office as part of a service report.

This mixed-reality system can also be used for hands-on training.

The construction industry uses ProG in the Trimble XR10 hard hat, which has a HoloLens 2 attached. Workers can view various stages of the building process, such as superimposing ductwork that will be added after all the beams are in place. A truck-engine manufacturer uses the same software to ensure all the varied configurations are assembled correctly.

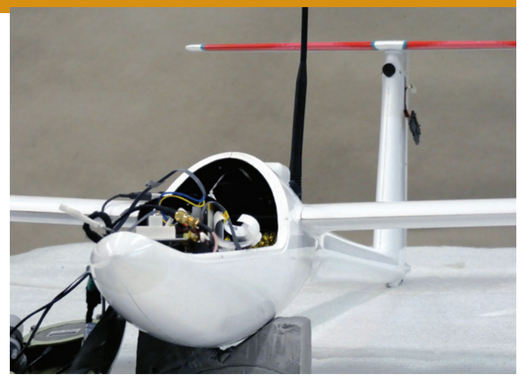
Any procedure that can be written down can be presented with ProG. ●

Hearing Silence from the Stratosphere

NASA microphone detects unseen air turbulence

Everything in the atmosphere can make a sound, but there's more to that sound than what our ears perceive. Much like how infrared light consists of frequencies that aren't visible to the naked eye, there's an audio analogue called infrasound. Infrasound consists of pitches too low to be heard by the human ear, between 0.001 and 20 hertz.

Turbulence can make air travel not only uncomfortable, but possibly dangerous. Though it isn't easily detected visually, clear-air turbulence has a definite infrasound signature. Researchers Qamar Shams and Allan Zuckerwar at NASA's Langley Research Center in Hampton, Virginia, realized that if air traffic controllers or pilots could listen in on these whirling vortices before airplanes encounter them, an alternate route could be plotted.

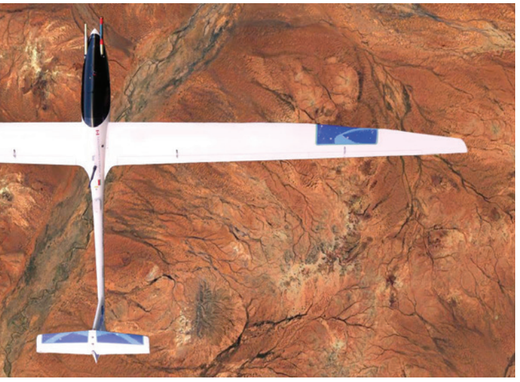


The HiDRON glider carries scientific instruments to the upper reaches of the atmosphere and keeps them working as it glides down. By using a NASA-designed infrasonic sensor to find and avoid turbulence, the glider can stay in the air longer. *Credit: Stratodynamics*

Their experiments began in 2007, but, unsurprisingly, initial tests showed that they couldn't grab just any off-the-shelf microphone and expect it to work with infrasound. The long wave frequencies tend to get overpowered by higher-frequency sounds, which results in interference. Shams and Zuckerwar began developing a sensor that could listen to these low frequencies in high fidelity. When these new microphones were placed in an equidistant triangular pattern, they were able to pick up and locate atmospheric turbulence more than 300 miles away.

By 2017, the technology received several accolades, but it hadn't flown aboard any aircraft. Interest from Stratodynamics Inc. of Lewes, Delaware, changed that. After the company won first prize in the unmanned aerial vehicle (UAV) competition at the 2016 Space Race Challenge co-presented by NASA, the team was invited to visit Langley, where they met Shams.

Stratodynamics realized that the microphone system had significant potential as an in-flight turbulence detection sensor and looked for opportunities to test the technology. After licensing the patents from NASA, the company began to implement the sensor on an unmanned stratospheric glider known as the HiDRON, designed by its Canadian affiliate, Stratodynamics Aviation Inc.



With the assistance of the infrasound microphone, the UAV can measure the intensity of turbulence in its path at a distance, and possibly detect thermal columns to keep the plane sailing longer. In 2020, the company's testing saw the microphone perform as expected. Even with rushing wind whipping past the UAV, the sensor could detect and characterize the low frequencies. Pending additional flight tests, the infrasound microphone will become a part of the standard atmospheric sensor package flown on the glider, and the team hopes the data provided will become ubiquitous in detecting and forecasting turbulence. ●

Typically launched by a weather balloon, the HiDRON has soared from over 100,000 feet in the air. Stratodynamics believes that with the infrasonic technology it licensed from NASA, it can further improve performance. *Credit: Stratodynamics*

Qamar Shams and Allan Zuckerwar at Langley Research Center designed a special infrasound microphone that could pick up the ultralow frequencies generated by turbulence in the skies. This technology is now being tested on the Stratodynamics HiDRON glider for both turbulence detection and aeronautical research. *Credit: NASA*

For Work or Play, Comfort All Day

The Energy Pro series of gaming chairs by Raynor Gaming incorporate two NASA spinoffs to keep users comfortable – Tempur-Pedic memory foam and Outlast cooling technology. *Credit: Raynor Gaming*

Two NASA technologies converge for more comfortable chairs

A new line of gaming chairs combines two NASA technologies to keep users comfortable during even the longest video game marathons.

Raynor Group, a major manufacturer of office furniture, has long incorporated Tempur-Pedic memory foam and Outlast cooling technology into office chairs, but the company is now extending the technology into other offerings.

Phase-change materials manage temperatures by absorbing, storing, and releasing heat as they change from solid to liquid and back. The technique for weaving microencapsulated phase-change materials into fabrics was developed in the late 1980s under Small Business Innovation Research funding from NASA's Johnson Space Center in Houston, which was considering the temperature-regulating fabrics for spacesuit gloves. Seeing potential, Outlast Inc. quickly licensed the technique and has since sold its fabrics for a wide range of applications.

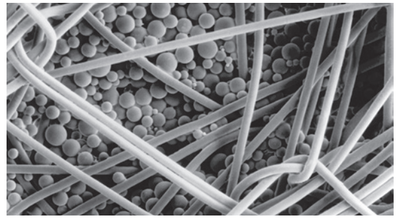
Memory foam was developed even earlier, in the late 1960s, part of an effort at Ames Research Center in Silicon Valley, California, to improve commercial plane crash survivability. Engineers developed an open-celled polymer foam and incorporated it into passenger plane seats. It was nonflammable and great at absorbing impact. Later NASA released the formula for what it called temper foam to the public. Two Scandinavian companies were among those who snatched it up, and they merged to form Tempur-Pedic, which brought its version of the foam to market after refining it over about a decade.

Raynor was introduced to Tempur-Pedic in 2009, and the two companies spent a year working out the right formulation for seat cushioning. Tempur-Pedic also introduced Raynor to Outlast, which it already used for temperature control in its mattresses. Raynor, located in West Hempstead, New York, now has an exclusive license to use Tempur-Pedic's foam in chairs, and it incorporates Outlast fabrics into many of its office chairs. Raynor sells the chairs to furniture dealers, as well as the government via the General Services Administration. It also makes several lines exclusively for big box stores like Staples.

In summer of 2017, the teenage son of a Staples' merchant asked his father if it would be possible to make a gaming chair with the cooling technology he heard was in some of Staples' office chairs. Staples passed the question on to Raynor, which built a prototype within two weeks, said Marc Saban, director of gaming for Raynor Group. After launching a gaming line for Staples, the company started Raynor Gaming in summer of 2018.

Tempur-Pedic foam is used in the seats of several of Raynor Gaming's chairs, and all of them use Outlast cloth wherever the user's body would stay in contact, sometimes in a double layer, Saban said, adding that he didn't know of anyone else using Outlast in chairs.

The company is now an official partner of several professional sports gaming organizations, including the NBA 2K League, Dignitas and the New York Excelsior Overwatch League team. ●



An electron micrograph shows how Outlast Technologies incorporated microencapsulated phase-change materials into cloth, a technique that was pioneered for NASA in the 1980s.

Hot Water on Demand

NASA expertise leads to improved in-home tankless water heaters

Tankless water heaters, which rapidly heat water as it passes through the unit instead of keeping it hot in a tank, have existed since the 1930s. However, they couldn't be used for an entire home because they drew too much power. David Seitz, CEO of Houston-based Seisco International LLC, wanted to make a better design. Seitz devised an electric tankless heater that could fully replace or work alongside a traditional water heater using digital controls to manage power draw – but he needed help to get it off the ground.

He turned to two former NASA contractors, who had built their expertise on spacecraft. The first, Thomas Harman, a contractor for Lockheed Corporation, helped install microelectronics in testing facilities at NASA's Johnson Space Center in Houston that would put spacecraft through their paces. After leaving in the late 1970s, he became part of the National Electrical Code, helping to create standards for everything from laboratory testing to home design.

The second, Louis Everett, was also a microelectronics expert, who had also worked as a consultant for Johnson. Everett helped develop code to improve the space shuttle's robotic arm. Everett took the knowledge he developed on this and other projects into consulting after he left Johnson.

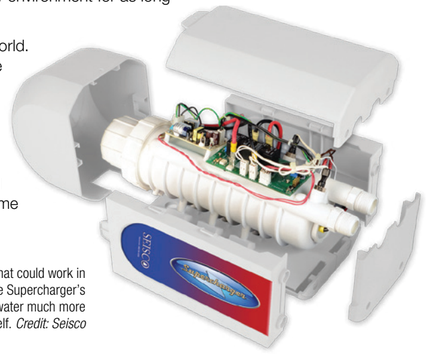
In the 1990s, Seitz brought on Everett as a consultant and approached Harman, asking how whole-home tankless water heaters could work within the bounds of the National Electrical Code. Harman would soon join the team as the company's head of R&D.

The Seisco team soon patented a new design that used microelectronics to keep the water from heating to dangerous levels, with Harman designing the circuits and Everett handling the code. Everett says working with embedded electronics is much like designing hardware for space. It's important to ensure that the technology can work in any environment for as long as possible.

The heater is now being used around the world. Harman says the original design for home use has since been expanded to heat water in apartments, office buildings, factories, and gas stations. Seisco is no longer making new heaters, but its technology helped open up the market. Several Seisco patents are expired and open to use, and multiple manufacturers now make whole-home electric tankless heaters. ●

In 1994, space shuttle Columbia carried experimental improvements to its robotic arm, testing microelectronics programmed by Louis Everett. Everett would go on to write code for the Seisco tankless water heater. *Credit: NASA*

The Seisco water heater's control board uses microcontrollers to ensure the 7000-watt heating elements can safely warm water almost instantaneously. Thomas Harman credits his experience with NASA in helping to design the necessary electronics. *Credit: Seisco*



Seisco offered water heaters that could work in conjunction with an existing heater. The Supercharger's specialized controls assist in heating water much more quickly than a tank by itself. *Credit: Seisco*

A New Doorway to Space

The Nanoracks Bishop Airlock can be attached to Node 3 and opened to space to release satellites and run experiments. It can also be detached and moved to different locations. Taking advantage of the opportunity to expose experiments to different elements such as sunlight or atomic oxygen, this flexibility enables a wide range of research possibilities. *Credit: Nanoracks*

The privately funded Bishop Airlock expands commercial access to the space station

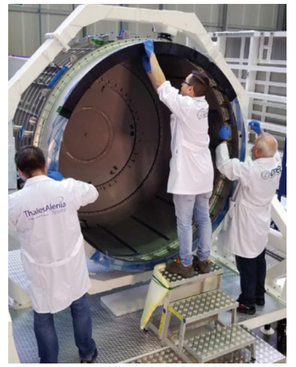
Anyone who has gotten a sofa stuck in a doorway on moving day knows how frustrating it is when there's no other way in or out. The doorways on the International Space station, or air locks, have worked just fine for 20 years. But as more researchers and companies wish to expand the scope and size of the projects they send into low Earth orbit, a larger doorway could help.

Opening a second portal to receive more shipments and deploy more satellites and experiments is the challenge a private company took up – Nanoracks LLC, headquartered in Webster, Texas. With support from NASA, the company built a new and different kind of doorway into space..

The Nanoracks Bishop Airlock Module will serve as another door to space, helping to move larger payloads on and off the station. This alleviates one bottleneck slowing down the deployment of new small satellites and CubeSats from the space station. Bishop has also significantly increased the amount of research that can be done in low-Earth orbit – research that helps us better understand the space environment but also has implications for Earth imaging, medical research, and biomanufacturing.

The new airlock is one of the first permanent commercial areas added to the space station and is attached to the port on U.S. Node 3, also called Tranquility.

The arrangement is part of NASA's strategy to offer more opportunities for U.S. industry on the space station with the goal of establishing a sustainable economy in low-Earth orbit, in which NASA will be one of many customers. This is allowing the space agency to prioritize deep-space exploration such as the upcoming Artemis Moon missions.



The Nanoracks LLC Bishop Airlock Module that was added to the space station has five times the capacity of the one other airlock currently in use on the station. The Japanese airlock (left) used to launch CubeSats is much smaller than Bishop (right). The privately funded airlock can accommodate significantly more satellites and autonomous experiments. *Credit: NASA/Nanoracks*

Bishop provides five times the capacity of the station's only other operational airlock being used to send things outside the space station, which is provided by the Japanese space agency, JAXA.

"That's more volume than could be either brought inside or taken outside," said Mike Read, manager of the space station business and economic development office at NASA's Johnson Space Center in Houston. Charged with supporting NASA's public/private relationships on the station, Read described the agency's allocation of the port to the new airlock as "a huge dedication of resources" that will serve public and private customers alike.

The bell jar-shaped airlock contains multiple rows of standardized tracks for mounting automated modules and other components for housing experiments, as well as electrical and data connections to run and monitor them. There are also six external mounting locations and a WiFi antenna to transmit data.

Bishop is designed to hold any combination of satellites and experiments, so each time it is opened to space, multiple satellites can be deployed, and passive experiments can run simultaneously. The robotic arm can be used to extract and launch satellites or mount external experiments. This flexibility makes it possible to alternate between Earth observation and astronomical study. ●

Communicating via Long-Distance Lasers

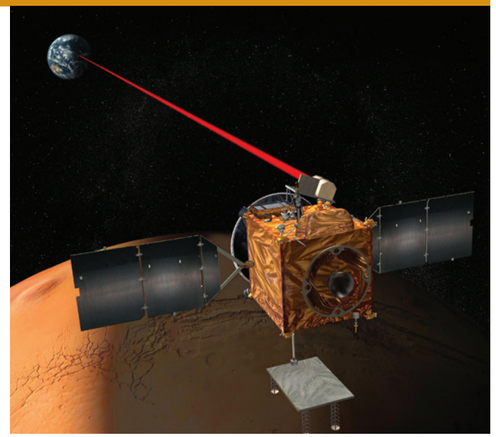
A NASA partnership made lasers viable for satellite communications

Visible light has been used to communicate for centuries, but now there's a new way to use light to communicate over even further distances and with far more accuracy – lasers.

Space is a perfect environment for laser communications, because there's no atmosphere or buildings to impede the beam's path. But before NASA could use this technology on deep-space missions, it had to be tested closer to home. In 2013, a demonstration on the Lunar Atmosphere and Dust Environment Explorer (LADEE) relayed video between ground stations on Earth and the orbiter. In testing, LADEE was able to transmit enough data to carry 30 HDTV channels. To further explore how this technology could work, NASA's Goddard Space Flight Center in Greenbelt, Maryland, partnered with the private sector.

Denver, Colorado-based BridgeComm, formerly known as BridgeSat, was founded in 2015 to dive into the opportunities presented by using lasers to communicate in space. They sent their proposal in response to Goddard's call for partners and ultimately won the competition, signing a Space Act Agreement soon afterward.

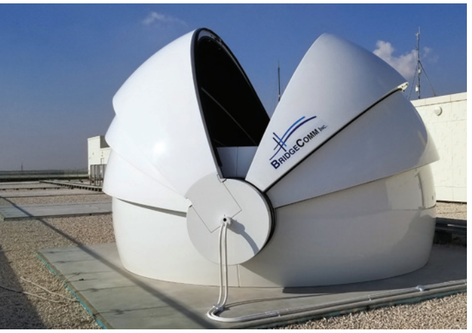
Over the course of this and subsequent agreements, BridgeComm engineers consulted frequently with their counterparts at NASA, facilitating their access to NASA's wide knowledge base. While working with Goddard, the company also made agreements with NASA Headquarters, NASA's Ames Research Center in Silicon Valley, California, and Glenn Research Center in Cleveland. With all these centers on board, the company applied NASA expertise to every part of its system.



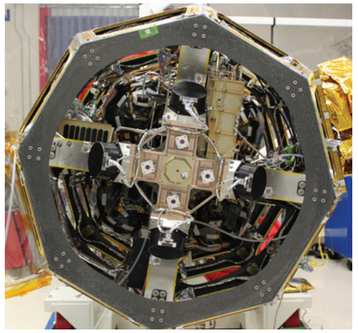
NASA is exploring the use of lasers to communicate over potentially interplanetary distances. Through collaboration with the private sector, future NASA missions could use a powerful beam to send data back to Earth. *Credit: NASA/JPL*

Compared to the wide area a radio signal can cover, lasers from space can only be received across an area the size of a football field. To allow ground stations to reliably pick up the signals from space, BridgeComm and NASA teams brainstormed a way to ensure the beam remained trained on a spot on the planet below. By mounting the entire laser system on a gimbal and using fine steering mirrors, the engineers could ensure the beam didn't wander. And while lasers can travel a great distance, they need to be powerful enough to travel potentially interplanetary distances. BridgeComm and NASA's amplifiers are able to keep the beams bright, while still small enough to fit on a satellite.

When the time came to renew the agreement with Goddard in 2019, BridgeComm didn't need the center's assistance anymore, as the company had successfully built out its own systems. BridgeComm's primary customers are those that need high-speed communications but don't want to compete for bandwidth on the already crowded radio channels, and the company is already contracted for two new satellite constellations. ●



Thanks to Space Act Agreements with various NASA centers, BridgeComm benefitted from NASA's wide knowledge base to develop their laser communication technology. The company's ground stations are able to transmit and receive data from satellites in orbit using visible light. *Credit: BridgeComm*



The demo laser system on the Lunar Atmosphere and Dust Environment Explorer orbiter could relay enough data for 30 simultaneous high-definition video streams between Earth and the Moon. The success of the test opened the door for further testing and development of "freespace" laser communications. *Credit: NASA Goddard*

Smart Glasses Focus Attention

Narbis improves concentration with NASA neurofeedback technology

The Narbis smart glasses set includes the glasses, equipped with three brainwave sensors; a Bluetooth-enabled amplifier on an armband; and a tablet with training programs. *Credit: Narbis*

A new pair of smart glasses uses a technique invented at NASA to measure users' brainwaves and tell them how well they're paying attention. Others have used the NASA formula to help people train their concentration, but Narbis' new smart glasses are getting quicker results.

The technique is based on neurofeedback – detecting brainwaves and showing users a readout of their own brain activity.

In the 1990s, Alan Pope, a scientist at NASA's Langley Research Center in Hampton, Virginia, came up with a way to translate brainwave output to characterize attention levels. To help pilots train their attention, he invented what he called an engagement index, a calculation based on comparing the strength of beta waves against alpha and theta waves. Pope's system then generated a number to indicate the level of engagement.

His team tested the technique and found that subjects who were shown their engagement level while performing a task were able to learn to control their concentration and outperformed control groups while reporting a lower perceived workload.

In the early 2000s, psychologist Domenic Greco licensed Pope's system and founded CyberLearning Technologies, using video games to help users improve control over their concentration (*Spinoff* 2003). His son Devon joined him in the business.

With time, though, they wanted to bring the technology to bear on real-life activities. In the months before Domenic's death in 2013, the father-son team came up with a solution: apply the same technology to glasses that users could wear while performing any task. The glasses would darken as the user became distracted.

Devon soon founded Narbis, of Ambler, Pennsylvania, to work on the idea. Patents on the NASA technology have expired, so no license is needed, and he said the glasses incorporate Pope's engagement index, as well as a couple other aspects of the NASA work.

Narbis glasses train the user to focus by darkening when attention wanders and clearing up when focus resumes. They can be used while performing virtually any task. *Credit: Narbis*

While the glasses never go dark enough to interrupt activity, keeping them clear is an effective real-time incentive for the user to maintain optimal focus, he said, adding that letting the user choose the task increases engagement and improves results.

The first prototypes went out to clinics in 2014, and iterations of the glasses have been in testing ever since. Results have been promising, with clinicians reporting results achieved in about half the time other neurofeedback techniques take. People who take medication for attention difficulties are coming off those drugs after about 20 sessions, Greco added, as opposed to the 30 sessions other neurofeedback usually takes.

The final product started shipping in August of 2020.

Greco said the core customer base will be home users who struggle with attention or just want to improve their concentration. He noted that about a fifth of parents of the 10 million U.S. children diagnosed with attention disorders are looking for options other than medication. ●

Modeling Airflows to Help Air Filters

NASA expertise improves air filtration technology

Whether trapping microscopic germs or an abundance of pet dander, air filters help homes and offices alike maintain a clean environment. With any technology, research and development can be a huge undertaking, but with a bit of help from NASA, a small business was able to turn its noisy air purifier into a quiet air-cleaning machine.

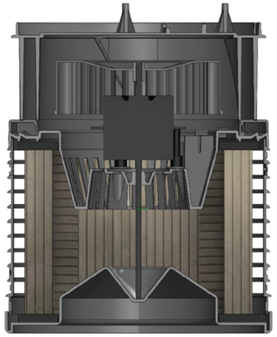
Health-Mor of Brooklyn, Ohio, got its start making vacuum cleaners in 1928, but in the early 1990s, it applied its vacuum cleaner know-how to build an air filter. Health-Mor put the Defender Air Purifier on the market in 1995, but there was room for improvement. The Defender was built into a chassis similar to the company's FilterQueen vacuum, and it shared one noticeable quality with its cousin: noise. One way to make the filter quieter and more efficient was to improve airflow. But to make these improvements, they'd need to redesign the Defender from the ground up.

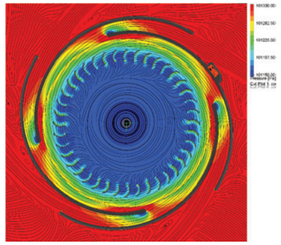
An Ohio regional industry group, the Manufacturing Advocacy and Growth Network (MAGNET) suggested that Health-Mor apply for the Adopt-A-City program they were working on with the local government and NASA's Glenn Research Center in Cleveland. From 2012 through 2016, MAGNET and local officials selected small businesses from around the Cleveland area in need of consulting, and Glenn would provide technical expertise to the firm for free.

Health-Mor was selected for the 2016 crop of Adopt-A-City finalists. Adam Wroblewski, who specialized in computational fluid dynamics (CFD) jumped at the opportunity to work on the project. NASA researchers use CFD simulations to model airflow around aircraft or spacecraft or fluid flows through engines. Wroblewski had just finished a project where he performed this work for jet nozzles, so he had a good idea where to start.

Wroblewski discovered that some slight modifications could bring Health-Mor close to its design goals. Removing some restrictive bodywork bumped up the airflow slightly, and extending the size of the blower fan improved it even more. Armed with that information, Health-Mor went back to the drawing board and fabricated a new fan system.

With the improvements, the filter moves 138 cubic feet of air per minute on just 85 watts of power. That's the same as an industrial floor fan, and enough to reliably clean a 300-square-foot room. The new fan design also moves air more quietly than before, because it's wider and doesn't need to spin as fast to achieve a similar result. As of 2019, the Defender had made $2 million in sales after the NASA improvements. ●

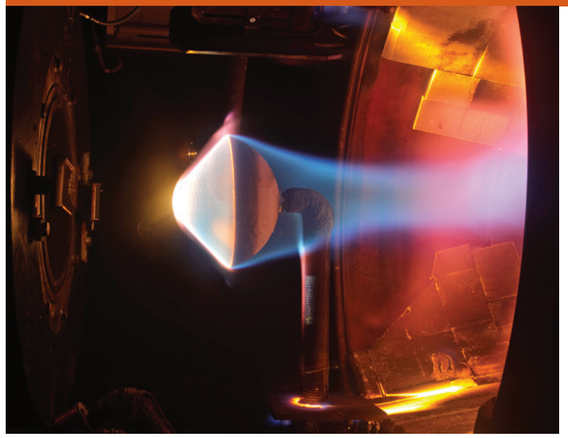




NASA engineer Adam Wroblewski was able to take 3D models of the Defender Air Purifier and run fluid dynamics simulations on them, uncovering ways to make the machine run smoother and quieter. *Credit: Adam Wroblewski/NASA*

The Defender Air Purifier has been on the market since the 1990s, but it recently underwent a redesign to take advantage of efficiencies found by NASA researchers under the Adopt-A-City program. *Credit: Health-Mor*

Taking Out the Trash, NASA-Style



The Arc Jet Complex at Ames Research Center tests thermal protection material with plasma like that generated during atmospheric reentry to make sure it will work effectively. InEnTec Inc. used agency research into nozzle and power supply designs when creating its plasma-assisted gasification technology. *Credit: NASA*

This cabin view of the space shuttle during STS-42 reentry shows the color of atmospheric plasma. Due to the compression and friction of the air, the molecules generate a very hot plasma which glows in the red-orange spectrum. NASA conducts tests on the heat shield and materials on spacecraft to make sure they'll deflect the damaging heat. InEnTec used some of the agency's research to design a plasma-assisted gasification process. *Credit: NASA*

Plasma arc technology for testing heat shields transforms garbage into reusable chemicals

The space station doesn't have curb-side trash pickup, but it does have access to a naturally efficient incinerator – Earth's atmosphere.

Astronauts pack trash into a no-longer-needed cargo spacecraft and allow it to fall into Earth's atmosphere. The extreme heat the spacecraft generates as it plunges forces the gas molecules to dissociate, vaporizing most of the craft and its contents.

Replicating this high-temperature trash processing on Earth is precisely what InEnTec Inc. is doing, with some help from NASA arc heater research and technology.

NASA uses heat shields when it doesn't want a spacecraft to vaporize – for example, when astronauts are inside. To test whether a heat shield can survive reentry, NASA had to recreate those extreme conditions.

Starting in the 1960s, NASA's Ames Research Center in Silicon Valley, California, worked to develop plasma arc heaters to generate the temperatures needed to put heat shields to the test. In 1965, the agency patented the segment-constricted arc heater, which has since become an aerospace standard. The breakthrough in the design was using individual copper discs to control the arc inside a tube, dramatically increasing the temperature. Cooling the heater while in use prevents the various components from melting.

InEnTec, based in Richland, Washington, used this research and design, as well as NASA research regarding coaxial current flow with specially designed inductors, to create its Plasma Enhanced Melter (PEM). The PEM transforms waste material into synthetic gas and other products.

With plasma-enabled gasification, the waste, called feedstock, is heated to extremely high temperatures, breaking down the carbonaceous material into basic molecules – carbon, hydrogen, and oxygen.

The molecules are separated and then converted into products that can be used to create anything from jet fuel to clothing. Any inorganic material that's left over, called slag, is added to super-heated glass. The resulting non-toxic substance is safe for a number of industrial uses, including building materials. The entire system generates no air pollution or toxic waste.

Started in 1995, InEnTec has installed 13 PEM systems around the world.

One facility, at the Columbia Ridge landfill in Oregon, was recently upgraded to convert medical and other waste into hydrogen for vehicles powered by hydrogen fuel cells. A chemical company, InEnTec's newest client, is working on recycling plastic waste. The plastic feedstock is converted into synthetic gas and intermediate materials that could be used to create new plastics.

Though developed by NASA decades ago, plasma arc technology is still used in this and other ways. Both the private sector and space exploration continue to benefit from the unique requirements of space travel. ●

Recalibrating Fine Motor Skills

Space app for testing fine motor skills touches down in the Apple App store

A touchscreen control panel similar to an Apple iPad seems like it would be easier to use than a panel of switches and buttons that must be flipped and pushed in the right order. But what if an astronaut's hand-eye coordination is slightly off? Will she still be able to operate the touchscreen with accuracy?

Research conducted by NASA proved what astronauts learn first-hand– fine motor skills are impaired during the first week in space. The human body undergoes an adjustment to functioning without gravity. However, it adapts quickly, and fine motor skills revert back to normal. Returning to Earth also interferes with fine motor skills, impacting touchscreen performance for tasks that involve pointing and tracing. Those problems can last up to a month, and it's possible this disruption could also occur after landing on the surface of the Moon or Mars.

The Reston, Virginia company Leidos Holdings Inc. developed the Fine Motor Skills (FMS) test battery app for the Human Research Program at NASA's Johnson Space Center in Houston, and it was used in research conducted on the International Space Station. Thanks to technical fellow Kritina "Tina" Holden, principal investigator, the agency has quantitative data that may help inform the design of equipment, procedures, training, and more to account for temporary impairment of motor skills. The FMS software is now available for testing fine motor skills on this planet.

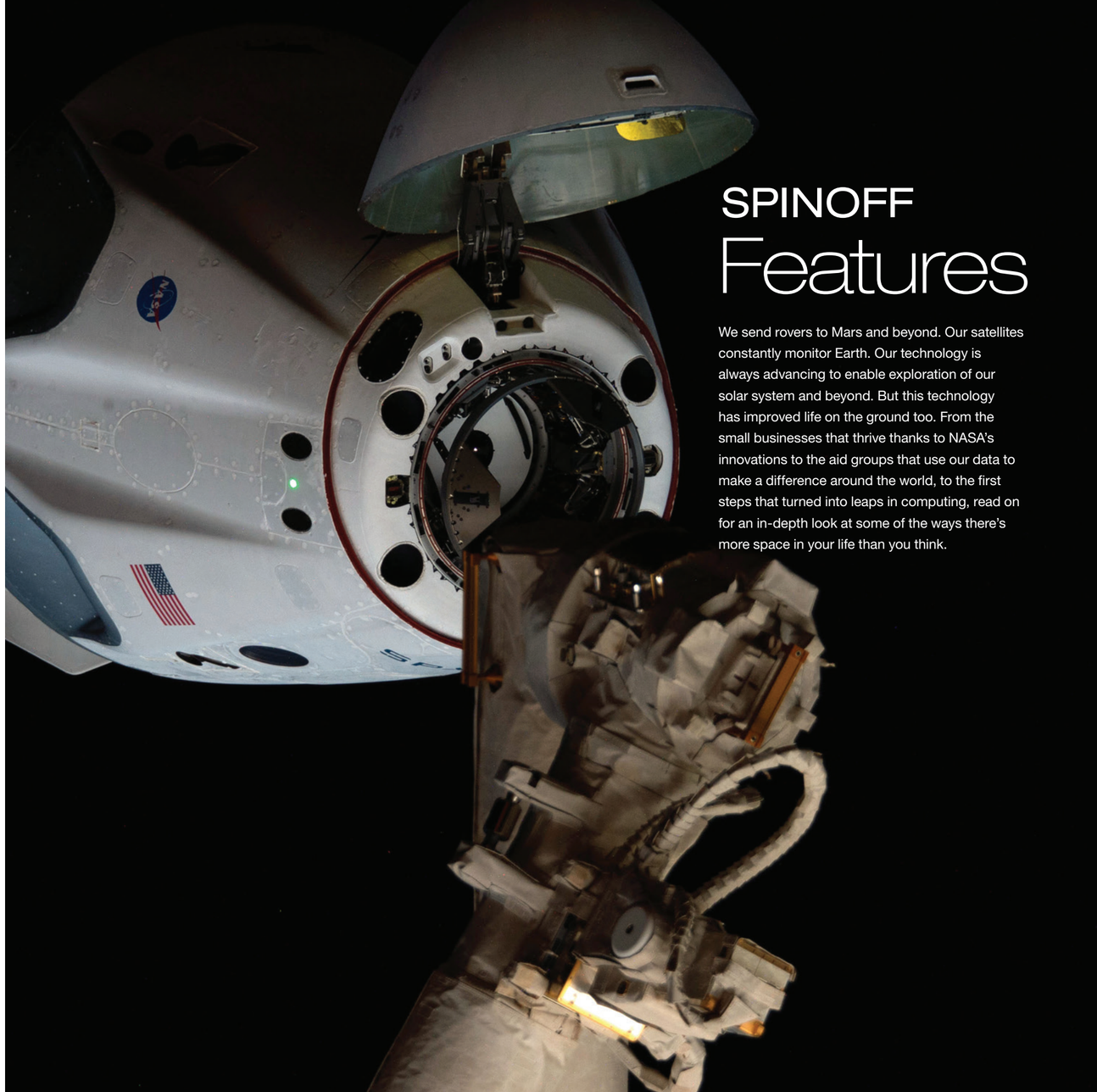
Holden and her colleagues are talking with researchers and physicians about numerous ways the app could support ongoing research and patient health. Some likely uses include training and testing the fine motor skills of surgeons, physical therapy for stroke patients, and monitoring recovery after traumatic brain injury. Anyone can download the app from the Apple App Store and test their fine motor skills, but in the near future, it's likely to be a tool for research studies.

Holden explained that the app can also be used to test skills under different environmental conditions. NASA is currently using it to study subjects' reach and accuracy when touching targets under G-forces in a centrifuge. The military is interested in using the tool to test the effects of CO_2 on performance. While there's no current plan to make changes to the test battery, it's possible an Android version will be available sometime in the future.

The Fine Motor Skills app is also available in the NASA Software Catalog. ●

NASA astronaut Scott Kelly performs the Fine Motor Skills test as part of his One-Year Mission. This task tested Kelly's ability to use fine motor skills – pointing, dragging, shape tracing, and pinch-rotate – on an Apple iPad during and after an extended stay in space. *Credit: NASA*

NASA astronaut Peggy Whitson completing the final of five Crew Autonomous Scheduling test sessions using an iPad to schedule a future workday. This is just one way in which crew members use touch screens in space, making fine motor skills essential for successfully completing a variety of tasks. *Credit: NASA*



SPINOFF Features

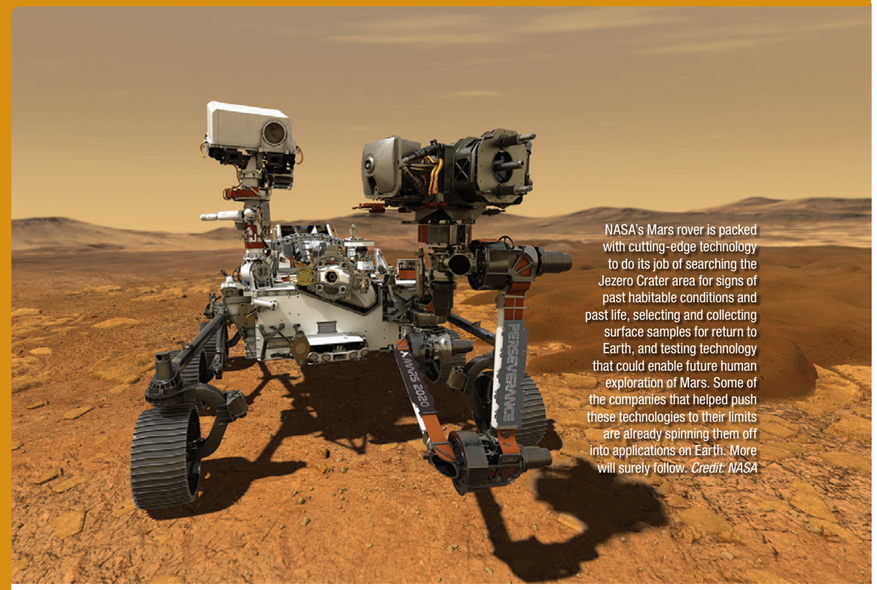
We send rovers to Mars and beyond. Our satellites constantly monitor Earth. Our technology is always advancing to enable exploration of our solar system and beyond. But this technology has improved life on the ground too. From the small businesses that thrive thanks to NASA's innovations to the aid groups that use our data to make a difference around the world, to the first steps that turned into leaps in computing, read on for an in-depth look at some of the ways there's more space in your life than you think.

The Rewards of Perseverance

Even before the Perseverance rover gets to Mars, the work that went into it is paying off on Earth

A laser-light sensor that can identify bacteria in a wound may sound far-fetched, but it's already becoming a reality, thanks in part to NASA's Mars Exploration Program. The technology is going to Mars for the first time on Perseverance, which launched in July 2020, but it's already detecting trace contaminants in pharmaceutical manufacturing, wastewater treatment, and other important operations on Earth.

That's not the only technology headed to Mars that's already paying dividends on the ground. Here on Earth, these innovations are also improving circuit board manufacturing and even led to a special drill bit design for geologists.

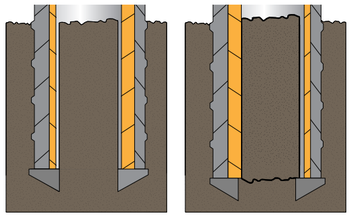


NASA's Mars rover is packed with cutting-edge technology to do its job of searching the Jezero Crater area for signs of past habitable conditions and past life, selecting and collecting surface samples for return to Earth, and testing technology that could enable future human exploration of Mars. Some of the companies that helped push these technologies to their limits are already spinning them off into applications on Earth. More will surely follow. *Credit: NASA*

Giving Geologists a Break

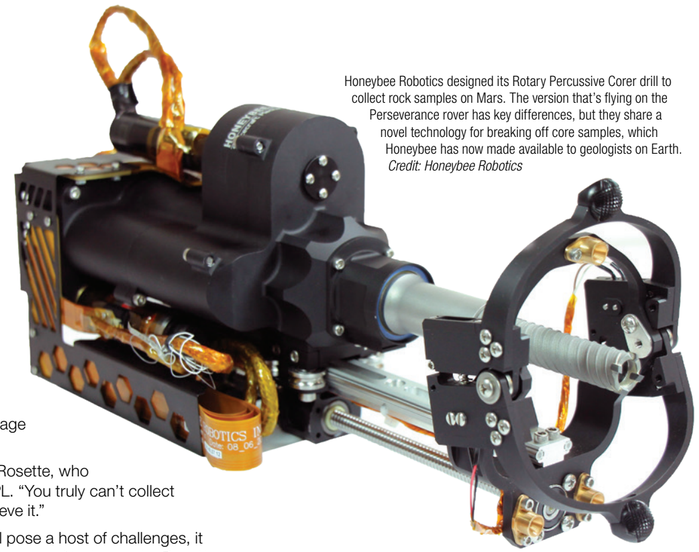
Honeybee Robotics has been working on robotic missions to Mars and other planetary bodies since the 1990s, including a number of projects funded by Small Business Innovation Research (SBIR) contracts from NASA's Jet Propulsion Laboratory in Southern California. One of the key contributions to come from that work has been sample collection technology, including a drill bit for extracting rock cores. Half a dozen coring bits developed from research that started more than 20 years ago launched into space for the first time, ready for use in the rover's turret, or "hand," at the end of its robotic arm.

On Earth, after drilling a core with a hollow bit, a geologist usually uses a screwdriver or other tool to break the sample off and pull it out. This can result in a fragmented or even contaminated sample. A robot required something different.



With an eye toward returning samples from Mars, Honeybee Robotics developed a bit that can break off and retain a rock core. Inside the outer bit is a breakoff tube that rotates independently. Both the inner and outer tubes are thicker on one side than on the other. In drill mode, pictured on the left, the thick and thin sides offset each other, forming a regular coring bit. In the right-hand picture, with the core drilled, the inner breakoff tube has rotated half a turn, putting both the thick sides on the right to shove the core leftward and snap it off. This also creates a little "step" at the bottom right that holds the sample inside the bit for retrieval. *Credit: Honeybee Robotics/Jennie Mitchell*

With SBIR funding from JPL, Honeybee Robotics developed coring drill bits that can break off and retain rock samples. The bits are flying for the first time on Perseverance and are available to geologists on Earth.



Honeybee Robotics designed its Rotary Percussive Corer drill to collect rock samples on Mars. The version that's flying on the Perseverance rover has key differences, but they share a novel technology for breaking off core samples, which Honeybee has now made available to geologists on Earth. *Credit: Honeybee Robotics*

New York-based Honeybee came up with a breakoff tube nested within a coring bit. After the core has been drilled, the breakoff tube rotates relative to the bit, shifting its central axis and snapping off the core. Unlike other breakoff methods, such as pinching the base of the core, the breakoff tube applies pressure along the length of the sample, reducing the risk of fragmentation.

Honeybee has supplied grinders, scoops, and other sampling systems that flew on previous Mars missions. This is the first time the company's coring bit technology is going to Mars, because it's the first time NASA has planned a future mission to bring samples of the Martian surface back to Earth. Perseverance will collect and package those samples.

"It's the key part of the sample return mission," said Keith Rosette, who managed the rover's sampling and caching system for JPL. "You truly can't collect a sample on Mars if you don't have a drill bit that can retrieve it."

While getting a sample return vehicle home from Mars will pose a host of challenges, it will let researchers do virtually unlimited testing with a wide array of instruments, Rosette said. "Rather than trying to bring all those instruments to Mars, it's less challenging and even more valuable to bring samples back."

Meanwhile, Honeybee has commercialized its patented breakoff bits in coring toolkits for geologists on Earth. The bits can be used with a standard drill, making the technology easy and affordable, said Kris Zacny, Honeybee vice president and director of exploration technology.

Honeybee has also been in talks with companies interested in using the bits for nuclear disaster remediation where it is too dangerous to send in human investigators, Zacny said. "If there are concrete tanks that are leaking, for example, then robots can go in and take samples to check radiation levels."

The technology was invented by Honeybee's late Chief Engineer Tom Myrick. "Tom would have been extremely proud that his invention made a difference to planetary missions," said Zacny.

A specialized drill bit that will let Perseverance collect samples of the Martian surface for return to Earth has led to a drill bit that makes it easier for geologists to collect rock samples on our planet. *Credit: Evgeny Kharitonov via Getty Images*

Home Videos from Mars

Collecting samples for return to Earth isn't the only first that engineers have planned for Perseverance. For the first time, NASA has built a system that could send back high-quality video of a rover's dramatic entry and landing sequence.

While the Curiosity rover sent back a series of compressed images showing the Martian surface during descent, Perseverance's entry, descent, and landing package includes six high-definition

This artist's concept shows the sky crane maneuver during the descent of the Curiosity Mars rover. Perseverance will use a similar landing technique, but for the first time, onboard cameras and a microphone will record the entire descent and landing. *Credit: NASA JPL*

As Tempo Automation built a circuit board for a Perseverance camera system, the company added new inspections and documentation to its production process and developed a novel preproduction tool. All these now benefit Tempo's customers.

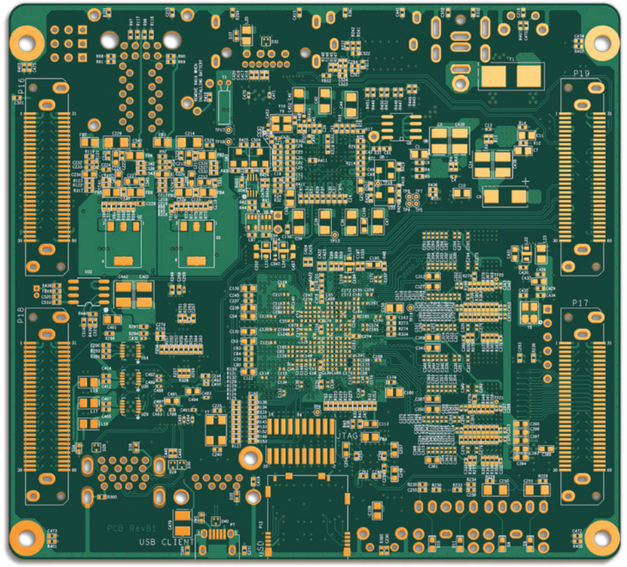
cameras and a microphone that aims to capture all the drama of the "seven minutes of terror" between hitting the outer atmosphere and touching down. In addition to watching the planet's surface, the cameras are positioned to watch the parachutes unfold and also to look back at the descent stage and down at the rover as the two separate.

The camera components are off-the-shelf models, but the circuit board that manages their interface and power was designed by JPL. It was then built by San Francisco-based Tempo Automation. Founded in 2013, just after NASA announced the Mars 2020 mission, Tempo used the work to improve its manufacturing processes.

As its name suggests, Tempo Automation's focus is rapid, automated production of printed circuit boards, even in small batches. One set of tools the company offers to that end is the process for making every component "traceable," to keep track of who touched it and what was done to it at each point in the board production process, as well as which component lot the piece came from. This information makes it easier to zero in on the cause of a problem and see what other boards might have been affected, said Tempo cofounder Shashank Samala.

To meet JPL's stringent documentation requirements, Tempo added X-ray images, ionic cleanliness data, and data from an automated optical inspection for every component, all of which is now part of the company's standard procedure.

A tool unique to Tempo is what it calls fabrication simulation – software that translates a computer-aided design (CAD) model into a photorealistic representation of what the final board will look like. A team was prototyping the tool when the JPL work began in early 2018, and that work helped them complete it, said Samala. It debuted the following year.



What looks like a photo of a printed circuit board is actually a computer-generated simulation based on computer-aided design files for a board-to-be. Tempo Automation developed this "fabrication simulation" capability while working on a circuit board for the system of cameras and a microphone designed to record the Perseverance rover's atmospheric entry, descent, and landing on Mars. *Credit: Tempo Automation*

The simulation lets customers check their designs for any issues or flaws before production begins, he said. "A simple mistake can cost a lot of money and time."

Chris Basset, who designed the circuit board at JPL, recalled that the simulator initially had some issues but came together nicely. "It's a really good tool, especially when you send design updates," he said. "Most vendors don't offer that."

While it was conceived to help customers finalize their designs, the company discovered that it was useful in-house as well. The manufacturing process can result in discrepancies between the original CAD model and the final product, Samala explained. The simulation "serves as a source of truth on the factory floor, to communicate the designer's intent. The first thing we look at is the simulation."

He said delivering a product that met NASA standards has helped the company get into several other space systems, including satellites and rockets.

Meanwhile, Basset looks forward to the moment the camera footage is beamed back from Mars after landing next year. "This is so far outside of what we usually do that it's super exciting," he said. "I can't wait to see those images."

Spinoffs from Mars!

NASA has been exploring Mars since the 1960s, pushing the frontier of innovation to get to the red planet and discover its secrets. This new technology has often found other uses here on Earth as well. A few highlights:

Generating Wind Power

Solar power is great until a Martian dust storm blacks it out. But there's another option for those blustery days: wind power. NASA helped design a low-maintenance wind turbine that can function in extreme conditions – on Mars or on Earth.

Ambulating Rugged Robots

In the 1990s, NASA came up with a way to combine stereo cameras and a 3D laser imager to help a rover see its surroundings. Today that system and other advances for Mars exploration help robots navigate terrain too dangerous for humans to go.

Suturing with Mars-Grade Materials

Bringing home a Martian sample requires a perfectly sealed container to prevent contamination. A soft, flexible, strong material keeps Martian dust from interfering with the seal and is great for heart surgery sutures and stents.

Making Clean Power

A human mission to Mars will require creative use of resources. A fuel cell that uses solar power to split water into oxygen for breathing and hydrogen for fuel is ideal. Technology based on that system now creates clean energy on Earth.

To learn more, visit: spinoff.nasa.gov/mars

Guiding Cars with Tech for Mars

Autonomous navigation on Mars requires "brains" made up of advanced neural networks and deep learning algorithms. But if the rovers can manage on another planet, putting the same tech in cars, drones, and toys here on Earth is a no-brainer.

Paving the Way for Hospital Robots

Mars rovers navigate alien terrain where they gather and analyze samples with minimal human help. Using the same skills, hospital robots can now do everything from delivering medications to ushering patients to appointments.

Detecting Methane Leaks

To search for life on Mars, we look for clues – like methane, which is usually created by microbes. But tools to sniff out tiny traces of methane on Mars now help detect leaks in natural gas pipelines on Earth.

Greening Up Drilling

How do you fuel a trip home from Mars? A system to break apart gases like carbon dioxide into its components could fill the tank. A similar system used on methane released from oil wells turns the greenhouse gas into energy.

Carbonating Beer

Technology created to fuel a journey home from Mars (now helping recycle methane from oil drilling) also found another use on Earth: capturing carbon dioxide emitted by fermenting hops and using it to put the bubbles in beer.

Ultraviolet Lasers Scan for Chemical Clues

Another technology whose roots reach far back into NASA's Mars Exploration Program is also flying for the first time on Perseverance and has many potential applications here on Earth.

When two longtime colleagues founded Photon Systems in 1997, research showed incredible promise for spectrometers – devices that use light to determine a sample's composition – operating at deep-ultraviolet (UV) wavelengths. These had the potential to identify bacteria or detect even the slightest chemical traces. But sources for light in the 220- to 250-nanometer range were too large, heavy, and sensitive to environmental interference, and had many other issues.

William Hug and Ray Reid set out to develop a miniature, lightweight, rugged deep-UV laser source for spectroscopy in the field. Their first outside investment came in 1998 from a pair of SBIR contracts with JPL, which was interested in a spectrometer that could detect nucleic and amino acids, organic materials that are foundational to all known life. Since then, the Covina, California-based company has received a number of NASA SBIR contracts, mostly with JPL, as well as funding from NASA programs aimed at developing instruments for planetary and astrobiology science.

Now the space agency will get the first big returns on its long investment in the technology: Perseverance is equipped with the Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument, which uses a Photon Systems laser to spot previously invisible clues in its search for signs of past life on Mars.

Deep-UV photons interact strongly with many materials, especially ones containing organic molecules. This results in higher detection sensitivity and greater accuracy when compared with infrared or even visible-light laser sources.

Deep-UV spectroscopy has been done in research labs, but Hug and Reid came up with a construction that was far smaller, simpler, and cheaper to build than any existing alternative. "Deep-UV lasers start at $100,000. That's why they're not used in industry," Hug said, noting that laboratory instruments using the technology might take up three laboratory tables and take a month to set up.

NASA funding, including JPL SBIR contracts for Mars exploration, helped Photon Systems make small, inexpensive spectrometers in the deep-UV range, where they're so sensitive they can identify bacteria. They're being used in pharmaceutical quality control, wastewater treatment, and more.

Currently, one of the most popular applications for Photon Systems' deep-UV spectrometers is pharmaceutical quality control, where the technology can measure ingredients and detect contaminants with extreme accuracy. *Credit: sanjeri via Getty Images*

One major challenge has been the level of perfection the technology requires. The same sensitivities that enable tiny, high-energy wavelengths to detect even a virus make them vulnerable to the slightest defects. A microscopic imperfection in a lens or other surface can disrupt or scatter them, and Hug said it has taken advances across multiple industries to meet the necessary standards.

Photon Systems focuses on two types of spectroscopy where deep-UV laser sources provide major advantages over longstanding spectrometer technology, and SHERLOC will use both. Fluorescence spectroscopy observes the light that most organic and many inorganic materials emit when excited by certain ultraviolet wavelengths, just like detergent glowing under a black light. Each emits a distinct spectral "fingerprint."

Raman spectroscopy, on the other hand, observes the light that a molecule scatters, some of which will shift to different wavelengths due to interaction with molecular bond vibrations within the sample. These shifts in wavelength can be used to identify the materials in a sample. The higher-energy photons of UV light elicit a much stronger Raman scattering signal from organic molecules than lower-frequency light. And because deep-UV light isn't present in natural fluorescence or in sunlight, using these very short wavelengths eliminates sources of interference.

In recent years, the company has started developing the technology into products, including handheld sensors and devices that monitor personal exposure to contaminants, as well as lab equipment. Their biggest markets now are in the pharmaceutical, food processing, and wastewater treatment industries, said Hug. Deep UV can identify and measure certain compounds at much lower concentrations than any other method, offering unprecedented precision in quality control, whether measuring the active ingredients in pharmaceuticals or ensuring the cleanliness of machinery and facilities.

In wastewater treatment, the technology can identify and measure contaminants, letting the operator tailor the treatment process and save on power for ozone infusion and aeration. "For a small wastewater treatment plant, the whole system pays for itself in less than a month," Hug said.

An application the military has invested in is identifying bacteria and viruses. Figuring out which bacteria are present in a wound, for example, would help pinpoint the right antibiotic to treat it, rather than using broad-spectrum antibiotics that risk causing drug resistance.

And rapid, affordable deep-UV spectroscopy holds promise for medical research, from diagnostics to identifying proteins, peptides, and other biological material.

"NASA has been a constant companion in our journey to date, and the laser is only part of the story," said Hug. "It's also the deep-UV Raman and fluorescence instruments we built for NASA and the Department of Defense over the years that are now providing breakthroughs for pharma, wastewater, and water quality in general, and now clinical testing for viruses."

On Mars, SHERLOC will look for organic materials and analyze the minerals surrounding any possible signs of life so researchers can understand their context, said Luther Beegle, principal investigator for SHERLOC at JPL. This will provide more details about the history of Mars and also help to identify samples for return to Earth. The instrument, which also includes a camera capable of microscopic imaging, will be able to map a rock's mineral and organic composition in high detail, providing lots of important data.

"We're going to make a brand-spanking-new measurement on Mars," Beegle said. "This is something that's never even been attempted before. We think we're really going to move the needle on Mars science and find some great samples to bring back."

Deep-ultraviolet (UV) spectroscopy detects certain compounds with extreme sensitivity and accuracy, but these systems have been prohibitively large and expensive for most applications. More than 20 years of NASA funding has helped Photon Systems bring down the cost of the technology and shrink it to handheld size. One of the company's deep-UV lasers is flying to Mars for the first time aboard Perseverance, which will use it to gather data about the Martian surface with unprecedented detail. *Credit: Photon Systems*

Photon Systems' deep-UV spectrometers offer wastewater treatment plants considerable savings by precisely identifying the levels of different contaminants and allowing treatment to be tailored. The company developed the technology with the help of long NASA funding, primarily with the aim of analyzing surfaces on Mars and other planetary bodies. *Credit: CUHRIG via Getty Images*

Medical Mission Control

Software that monitors astronaut health in space now monitors high-risk patients at home

NASA created a data analysis and distribution program to manage the vast amounts of information streaming to and from the space station. Ejenta licensed that software and turned it into a remote health-monitoring system, enabling healthcare providers to monitor patients from afar. All health data is securely stored in one place for easy access by the patient and care providers. *Credit: Hiraman via Getty Images*

When chronic pain flares, the trip from your door to the doctor's office can seem as difficult as getting from Earth to Mars. The same could be said for the challenge faced by an elderly grandparent going to post-surgery checkups or the frequent office visits required for conditions such as diabetes. At times like these, a spacesuit would come in handy.

When astronauts go on spacewalks, their spacesuits contain numerous sensors that monitor body temperature, heart rate, how much they sweat, and more. That data is automatically sent to NASA and distributed to the flight surgeon, biomedical engineers, and others. The ground-based crew uses that information to guide its support efforts – maybe giving a reminder to drink some water to avoid dehydration or take a short break to lower heart rate. The same remote health monitoring is now used on this planet in a system called Ejenta.

"We've applied the technology to various health monitoring situations, and it functions in a way that's very similar to the system at NASA," said Rachna Dhamija, CEO of Ejenta Inc. The customizable operating system is tailored to each individual, creating an intelligent agent based on each patient's profile. Building on the sophisticated algorithms and machine learning developed by NASA, the artificial intelligence system is able to "learn about the patient through data from wearable and wireless devices, adding to medical records," she said.

The cloud-based program employs off-the-shelf health and fitness monitoring devices to collect important health metrics. It then saves, analyzes, reports on, and distributes information to the patient and the entire medical team. Just as NASA cares for astronauts, an individual health plan determines what's monitored and how that data is reported and distributed.

And as with a spacewalk, the data is compared to target metrics to identify progress or issues.

The nurses and doctors, like a NASA ground crew, receive reports that include risk assessments and the steps necessary to mitigate any minor issue before it becomes a serious problem. The patient might get a reminder to take medication at a specific time or perform daily physical therapy exercises.

Custom software automated data collection from the space station, distributing it across NASA. Under exclusive license, that same program is now organizing and disseminating patient data for healthcare systems.

Ejenta can also integrate chart notes, clinical records, lab results, and more to create a comprehensive medical history that will reduce false alarms and miscommunication.

Healthy at Home

Ejenta uses a Bluetooth, WiFi, or cellular connection to transmit health measurements to the custom smartphone monitoring app. The data is automatically sent via an encrypted connection to the individual's intelligent agent. That ongoing flow of information replaces an office visit with a phone call or video visit to discuss recent vital signs. And patients can check on their performance against improvement benchmarks at any time.

Multiple studies conducted with healthcare provider Kaiser Permanente, an Ejenta customer, provide evidence for the system's potential benefits for treating serious health conditions such as heart failure and high-risk pregnancies. Doctors were able to catch problems early before it reached a crisis that required a hospital stay. For example, pregnant women were less likely to develop gestational diabetes and had fewer pre-term births and C-sections.

"Patients can stay healthy at home, reducing the number of times they go into the emergency room or the hospital for critical events," said Dhamija.

Maarten Sierhuis is Ejenta's chief technical officer. Sierhuis helped develop the behind-the-scenes programming that collects, evaluates, and distributes data when he worked at NASA's Ames Research Center in Silicon Valley, California. That work evolved into NASA's Orbital Communications Adapter Monitoring System, which has been in use since 2008.

"It sends all data to and from the International Space Station, including any medical data," said Sierhuis. "It's sorted and distributed automatically to all the different flight controllers, depending on who needs what."

Ejenta negotiated exclusive worldwide license for the software, which NASA called Brahms, and for all related applications developed by the agency between 2000 and 2012. The San Francisco-based company is the sole distributor of the program for commercial, government, research, and academic use outside the agency.

Taking Control

The monitoring app handles all that information flowing to and from patients, but the company is working to develop a voice-based interface to make accessing information easier. "What do I need to do next?" can prompt patients to take medication at a specific time or perform physical therapy exercises. "How is Mom doing?" can elicit an update to a designated caregiver.

Compliance with patient-privacy laws is of paramount importance, so every part of the data-transmission process is encrypted, according to Dhamija. Ejenta has to sign a data protection agreement with the health provider. That means patient information must be encrypted and authenticated so only authorized individuals can access it.

Voice-activated systems already exist, but they don't meet the legal privacy requirements for patient data.

"What's exciting now is that we're working with Amazon to have a compliant voice-based agent that the patient can speak to," said Dhamija.

The company also continues to improve the system with the most current and best medical practices available. For every illness the program monitors, medical professionals in those fields contribute expertise to the knowledge database. This ongoing development of the program's artificial intelligence means the care teams have comprehensive reference data in addition to their own experience.

Sierhuis said this kind of remote monitoring has been quietly growing and expanding over the past 10 years, as telehealth has moved from novelty to commonplace. But many people aren't aware of Ejenta because the program is incorporated into the healthcare systems that use it. Some of the largest healthcare providers in the U.S. use Ejenta to monitor high-risk conditions when a care plan requires the medical team to monitor multiple data points. While an integral part of the data-sharing process, it isn't like a fitness app that can be downloaded. It must be used in conjunction with a medical plan and care team.

"One of the amazing things about NASA is its ability to do research and create technology that is spun out and improves the U.S. economy," said Sierhuis, "making it possible for people to do things that otherwise would not be possible. We now have a care team that's just like in mission control." ●

Remote patient monitoring allows care providers and patients to access comprehensive health information at any time. Ejenta developed a proprietary system leveraging NASA technology to do just that. Wearables and medical devices automatically add information such as blood pressure readings. The patient app can access records and remind users to do anything from exercising to taking medication on a schedule. *Credit: NataliaDeriabina via Getty Images*

Collecting, sorting, and distributing data from the space station to all the departments and individuals at NASA who need it inspired theagency to automate the process. Called Brahms, the software is under an exclusive license to Ejenta for the collection and distribution of patient data according to a tailored remote monitoring plan. *Credit: NASA*

In the Right Hands, NASA Satellite Data and Analysis Make Earth Better

NASA data and imagery aid humanitarian and environmental efforts

"That original image alone was able to shift the perspective of a lot of people,"

Dan Hammer, Earthrise Alliance CTO

The first photo of Earth rising over the horizon of another celestial body was captured on December 24, 1968, by astronauts on Apollo 8, the first crewed mission to the Moon. *Credit: NASA*

The number of illegal gold mines in the Amazon is increasing so fast that activists have turned to satellite imagery to identify them. Still, with thousands of new mines a year, the work was overwhelming scientists at Earthrise Alliance – they needed more hands on deck. That's how ninth graders in Weston, Massachusetts, began locating illegal mining activity in Brazil's protected Yanomami territory.

Earthrise is one of numerous organizations getting Earth-observation images, data, and analysis – much of which NASA makes available for free – into the hands of people working on sustainability projects. These efforts by many different aid groups are tracking illegal mining, deforestation, and groundwater resources and informing the decisions of small farmers and governments trying to support them in regions that are feeling the worst effects of climate change.

Earthrise was working with Survival International, a group that has been reporting on illegal mines in the Yanomami territory for years. Miners bring disease, like malaria and tuberculosis, which can devastate local tribes that have had little contact with people outside their communities, according to Survival International. The highly contagious novel coronavirus now also threatens the region. In addition, the mines themselves pollute the land and waterways with mercury and other toxic substances.

Earthrise illustrated a striking rise in the number of new mines in the area in a graphic for Survival International. A few months later, shortly before schools across the United States closed in early 2020 amid the global pandemic, Earthrise asked Weston High School freshmen to comb Earth-observation data for environmental stories.

Examining satellite imagery from NASA, the European Space Agency, and the company Maxar Technologies, the students identified previously unreported illegal mines. The program is part of the Earthrise Education initiative, which provides students with an internet-based tool to use satellite imagery to investigate real problems that are in the news.

Founded by former NASA officials, Earthrise gave satellite data from NASA and other organizations to Massachusetts ninth graders, who used it to identify illegal gold mines in Brazil. The organization also helps conservationists and decision-makers use Earth imagery and data.

Headquartered in Washington, D.C., the Earthrise Alliance was founded in 2019 by former NASA officials as a merging of several projects that were using space resources to improve environmental conditions on Earth. The organization's chief technology officer, Dan Hammer, previously worked as a presidential innovation fellow with NASA's chief technology officer for information technology, where he made NASA data more accessible to the public.

A ninth grader at Weston High School in Weston, Massachusetts, scours satellite imagery provided by the Earthrise Alliance to locate illegal gold mines in the Yanomami protected territory of the Amazon rainforest in Brazil. Founded by former NASA officials, Earthrise is helping students engage with emerging environmental stories through Earth-observation data. *Credit: Earthrise Education*

"Satellite data can be complex. Making the data accessible and usable gives the local users more power to control their future."

Brian Killough, Langley Research Center

"We offer additional perspective, which was the idea of Earthrise in the first place," said Hammer, referring to the Apollo 8 photo for which the organization is named. Taken during the first crewed mission into lunar orbit, the photo shows Earth rising over the Moon's horizon, giving humanity a first glimpse of the home planet from another celestial body.

"That original image alone was able to shift perspective for a lot of people," Hammer said. "We're offering that perspective for emerging news events, the spaceship Earth perspective."

Self-Reflection

NASA has been looking back at Earth since the agency was established. In 1960, the agency began sending satellites into orbit to capture Earth images to improve weather predictions and maps. In 1961, Alan Shepard caught a view of Earth as the first American in suborbital space with Project Mercury.

Astronauts in the Apollo program in the 1960s and '70s received photography training, not only to learn how to use the equipment, like cameras bracket-mounted to their spacesuits, but also to develop an eye for science images. These efforts led to the Earthrise photo and other famous images, including the iconic Blue Marble shot.

Images from these early Mercury and Apollo missions were the inspiration for the Landsat Program, which in 1972 launched the first satellite tasked specifically with observing and collecting data on Earth's landmasses. The program has been in continuous operation since then, in partnership with the U.S. Geological Survey, which currently operates Landsat 8.

Today NASA has a fleet of satellites gathering Earth data, in addition to ambitious airborne and ground-based observation campaigns. Other governments and private companies have billions of dollars' worth of satellites looking back at Earth. NASA also has the resources to process this data and develop predictive models and analysis.

This Landsat 7 image of Guinea-Bissau, a small country in West Africa, shows the complex patterns of the country's shallow coastal waters, where silt carried by the Geba and other rivers washes out into the Atlantic Ocean. *Credit: NASA/USGS EROS Data Center*

The agency makes its Earth data available for free to the public. In some cases, organizations are working directly with NASA, benefiting from the agency's computing power, modeling, and analysis. Organizations can also access the rapidly increasing Earth-observation data from the space agency and other governments and companies around the world.

Striking Gold, Helping Farmers

The problem of illegal gold mines isn't unique to Brazil. It's a global phenomenon that gets worse when gold prices rise.

In Ghana, environmental officials used Landsat data and algorithms developed by NASA to identify hotspots of illegal mining activity and revoke licenses from scores of companies collecting gold while avoiding environmental oversight and taxes.

Davis Adieno, who oversees the collaboration from Nairobi, Kenya, where he is program director for the Global Partnership for Sustainable Development Data, said the project is also forward-looking.

"The Ghanaian government is using this data to communicate the impact of illegal mines, but also, more importantly, how areas that have already been impacted could be recovered," he said.

Working with the Global Partnership and other partners, NASA's Brian Killough produced the initial data cube platform for five African countries – Ghana, Kenya, Sierra Leone, Senegal, and Tanzania – tailoring it to specific projects and training initial users. The successful model has now been scaled up for Digital Earth Africa, which makes free Earth-observation data available and usable in an increasing number of countries across the continent.

Data cubes are stacks of satellite data configured to allow the use of powerful cloud computing and rapid analyses, Killough explained. Satellite data from many days or years can be organized into a cube, with dimensions of space (latitude and longitude) and time. These cubes are made of small pixels that hold data at a scale of 30 meters – about the size of a baseball diamond – which is Landsat's resolution. Once in a cube, it is much easier to analyze and apply the data.

Killough and his team at NASA's Langley Research Center in Hampton, Virginia, work directly with the users of the data resources they've created.

"We help them interpret the data and adjust the tools for their needs," he said. "We also conduct training in each country, where we give people an understanding of the data and tools and let them use it on their own."

Adieno said Killough "introduced what is possible – what type of data is available, the duration, what you can actually do with the infrastructure, with the algorithms that are available – which helped the countries identify who was best-placed to use it."

In most cases, the satellite data tools are being used by people who have already been working with satellite imagery, but with less powerful capabilities and extremely cumbersome and often untenable downloading and processing times.

Adieno said officials in Senegal purchased private data for their project but then later moved to the data cube infrastructure for their analysis. "The results were more or less the same, which means they didn't need to spend that money," he said. "The value here is access to free, open source satellite data that's analysis-ready."

Officials in five African countries are using a NASA-developed satellite data tool to identify illegal gold mines and conditions on the ground for small farmers struggling with climate change. Parts of the program are expanding to cover more countries across Africa.

A legal gold mine in Ghana shows some of the effects mining has on the landscape and environment. Illegal mines, which operate without environmental oversight, are often situated close to legal ones, and the water pools are more irregular or divert to small rivers. Ghanaian officials have shut down scores of illegal gold mines they identified using NASA satellite data and NASA-developed analysis tools. *Credit: Jordi Perdigó/Global Partnership for Sustainable Development Data*

Killough agreed. "People in the developing countries we've been working with recognize that satellite data could have a huge impact," he said. "But they have struggled with the preparation and the understanding of how to directly apply it to their applications. That's where I think we've made great progress."

The data resources are "certainly very efficient and effective," said Victor Addabor, who heads Ghana's National Disaster Management Organization.

Addabor worked with Killough to use Landsat data to identify the rate at which small farmers in the country's north are adopting new growing techniques, like using drought-resistant seeds. This type of information helps the government determine the best ways to support small farmers in remote areas who are making decisions individually while also playing a major role in the country's food security.

"That One Right Decision"

Indeed, unlike large agricultural producers in Europe and the United States, the vast majority of farmers around the world are working small plots of land, feeding much of Earth's population without coordination. These farmers are disproportionately affected by decreasing water resources and rising temperatures.

"In many places, if farmers don't make that one right decision, it can mean the whole year is incredibly challenging for them. It can mean that the kids don't go to school or families don't have enough to eat," said Eliot Levine, director of the Environment Technical Support Unit at Mercy Corps.

The Portland-based organization has been providing humanitarian relief around the world for decades and, more recently, is working with NASA on a partnership that uses satellite data to support science-informed policy and sometimes deliver information directly to people who need it.

Mercy Corps and NASA are collaborating in Kenya to reach farmers with a combination of precise weather and agronomic information. The work is part of Mercy Corps' AgriFin program, which focuses on building the capacities of smallholder farmers, using cellphones and texting technology to deliver information about weather forecasts, seed types, financial products, market prices, and other relevant resources.

"Through our partnership with NASA, we are providing farmers with information and tools they have never had access to before," Levine said.

"Should you plant now or wait? Water now or wait because rain is coming? Farmers need access to information," Levine said. "We envision a future where every smallholder farmer prospers in a digitally interconnected world."

The effort is part of a growing collaboration between NASA and Mercy Corps, a partnership that began in 2015 with an early project to map groundwater resources in Niger and was formalized in 2019 with a Space Act Agreement.

Shanna McClain, global partnerships manager at NASA Headquarters in Washington, said the agency was looking to "engage with partners that it hasn't worked with in the past in the hope of achieving new ways of understanding complex human and environmental challenges."

As the collaboration with Mercy Corps matured, McClain and Levine saw increasing possibilities for future work, as they had hoped they would.

Mercy Corps is collaborating with NASA through a Space Act Agreement, using satellite data to inform its humanitarian aid work and sometimes to pass on relevant information – about weather patterns or groundwater, for example – directly to farmers in Africa.

Patricia Nthenge, a farmer in Kenya who is participating in Mercy Corps' AgriFin program, stands among her pigeon pea crop. In collaboration with NASA, AgriFin is incorporating precision satellite weather data into the information and resources it delivers to smallholder farmers in Africa. *Credit: Mercy Corps*

"We didn't just want to work with a new type of partner," McClain said. "We wanted to see the magic that comes only from partnership."

The formal agreement "essentially helps recognize our interest in doing this work as a shared endeavor," she said, noting no money is changing hands. "We're putting in an equal amount of funding and capacity."

NASA scientists have worked with Mercy Corps from their desks and at the sites of international projects. The agency provides Earth science insights, in addition to data and analysis that Mercy Corps wouldn't be able to produce on its own.

Together, NASA and Mercy Corps are helping to strengthen the resilience of communities around the world.

Earth Data for Earth

Earthrise estimates that more than half a trillion dollars has been spent on public and private satellites looking back at our own planet, primarily for military intelligence and profit-driven fields like commodity trading.

Earthrise, along with Digital Earth Africa and Mercy Corps, is repurposing this technology.

"There's value that filters down when you're fundamentally aware," said Earthrise's Hammer.

"We're leveraging the hundreds of billions of dollars of existing investment for Earth literacy."

With Earth-observation data, people can assess how their own lands are changing and what they can do to alter the direction of the change.

"Satellite data can be complex," NASA's Killough noted. "Making the data accessible and usable gives the local users more power to control their future." ●

Cleaning Up a Toxic Legacy

System for removing toxins from buildings is repackaged to clean up contaminated sediment

NASA created technology that absorbs toxins from sediment and groundwater. A company licensed it and now sells a system that is both cheaper and more effective than traditional cleanups.

"Whatever we do on Earth has to be sustainable"

Sergie "Serg" Albino

Credit: alexionas via Getty Images

Jackie Quinn had an idea.

What if the system NASA developed for removing contaminants from building paint could also be used to clean up the environment around NASA field centers? In her quest to find out, the environmental engineer demonstrated typical NASA resourcefulness, starting out with a couple of plastic drinking straws she grabbed from a cafeteria at the agency's Kennedy Space Center in Florida.

The contaminants she was working against were polychlorinated biphenyls, more commonly referred to as PCBs. When the molecules were first developed and manufactured into multiple formulas, they were added to paint because they are non-flammable and can withstand temperature extremes. That meant paint wouldn't crack, peel, or catch fire, all important qualities for buildings located near rocket launches.

But PCBs can also have negative effects on humans and animals, in particular by changing how their hormones function. This can cause problems in growth and development, often resulting in physical and mental developmental issues.

"Nobody set out with the intent of hurting anyone when they developed PCBs," explained Quinn. "We just didn't know. But when you do know, you've got to go fix it. That's what we're trying to do."

Banished but not Vanished

PCBs are rarely heard about, partly because they've been banned since 1976. But the cleanup has been difficult, so PCB contamination of soils, water and the food chain remains a worldwide problem. According to a 2016 report from the United Nations' PCB Elimination Network, PCBs are currently the most globally widespread manufactured contaminant.

These molecules were used extensively in a wide array of applications, and as a result, they can be found all over the world leaching out of landfills and into the environment, making their way into soil and groundwater sources.

A 2009 study by the Environmental Protection Agency (EPA) found that, in tissues sampled from fish from 500 lakes around the U.S., every single one had detectable levels of PCBs.

Credit: ecoSPEARS

"We really have to think about the food, air, and water we're consuming on a daily basis. Is it clean?" said Ian Doromal, executive vice president and cofounder of ecoSPEARS. He is on a mission to use NASA technology to remove human-generated contaminants from the environment.

"People are starting to realize that this is not just something that happened in the past."

Because PCBs are hydrophobic – resistant to water – they gravitate to soil and sediment. Experiencing minimal degradation over time, they remain there until removed. That's why they're classified as a "persistent organic pollutant," or a "forever chemical." Until now, no cleanup process has been able to completely remove PCBs from an ecosystem.

A Better Eco-Trap

To remove PCBs from paint and other elements in its buildings after hurricane damage in 2004, Kennedy devised a system that uses a benign reagent, or a reaction-causing substance, to attract and trap the contaminants (*Spinoff* 2011). Quinn wanted to see if the technique could be adapted to get the contaminant out of the water near the buildings, too. As a first attempt, she heat-sealed the ends of her drinking straws, filled them with the reagent, capped them and placed them in a liquid containing PCBs.

It worked in a matter of hours.

"We saw a decrease in the amount of PCBs outside the straw and found PCBs inside the straw," she said. Subsequent experiments in several natural waterways proved the technology effective.

Based on Quinn's experiment, Kennedy developed a spike-shaped polymer tube called the Sorbent Polymer Extraction and Remediation System (SPEARS). When Sergie "Serg" Albino, CEO and cofounder of ecoSPEARS, learned about the technology, he saw incredible potential – so much so, he named his company after the NASA technology.

"The SPEARS work like a sponge," Albino explained. "Individual spikes are inserted into a mat structure, and you press it into the sediments. You leave it there for a certain amount of time, and the SPEARS absorb the PCBs or other chlorinated contamination from water and sediments. It gets absorbed into the reagent that's inside the SPEARS. When they're removed, the molecules are taken out of the environment permanently."

Among the most contaminated and difficult areas to remediate are seaports, according to Albino. A common technique, dredging to remove sediment, disrupts port business and damages the ecosystem. In addition to limiting shipping activity, the dredging scoops up the sediment layer containing plant and animal species.

Using the Port of San Diego, an ecoSPEARS client, as an example, Albino underscored the cost of environmental damage.

"There's sensitive eelgrass in California waters. If you were to dredge all that up just to get rid of the PCB contamination, you're paying four times more because you have to reconstruct the eelgrass," he said.

On top of that, whatever life forms are left behind or move in later will be exposed to the PCBs left by the debris plumes created during the process. Microbes and small aquatic species absorb the PCBs, so the fish that eat them also become contaminated. As each new predator consumes a contaminated food source, the PCBs accumulate and biomagnify every step of the way.

Innovation at Last

Sequestration in the form of capping is supposed to hold toxic material in place, preventing it from entering the food chain. But it's unreliable. An example of this came to public attention when the caps in San Jacinto waste pits in Texas were moved or damaged by Hurricane Harvey and subsequent flooding. The PCBs and other contaminants flowed onto residential property and exposed a wide area to the toxins.

"The PCBs, the contamination is the bad guy in this," said Albino. "But the lack of innovation is an even worse enemy. The folks in this trillion-dollar industry have decided there's really no good technology for it. So, they continue to dig, transport, and dispose."

Albino and his team negotiated an exclusive license in 2017 for the NASA-developed SPEARS, branding their product ecoSPEARS, and are making it an integral part of an environmentally sound PCB removal process. In addition to improving the original design, the company has developed its own proprietary reagent for containing the toxins.

The company is now piloting a new method for destroying PCBs on site. This technique breaks down the chemicals at the molecular level, transforming them into non-toxic compounds. The extraction and elimination processes work in water and soil. This alternative can eliminate the costs of removing and shipping contaminated material to an approved landfill site for storage or burning it, which pumps pollutants into the atmosphere.

Dollars and Sense

Clients using this new technology for their remediation projects include the Department of Health in Hawaii, a pulp and paper company, and a Fortune 500 multinational oil and gas company. EcoSPEARS is partnering with the engineering and construction consulting firm Black & Veatch on cleanup of an EPA-designated Superfund site in Florida, one of a number of projects in the company's growing portfolio of practical applications that prove the science behind ecoSPEARS.

Entities responsible for environmental cleanups are paying attention. Among these is the Port of San Diego and its Blue Economy Incubator program, which supports entrepreneurship, fostering sustainable aquaculture. In June 2019 the port kicked off a $200,000 cleanup pilot project with ecoSPEARS. The United Nations and its PCB Elimination Network are also partnering with the company to help achieve the U.N. Sustainable Development Goals to eliminate PCBs by 2028. The company was also accepted into the Clean Water Accelerator program of Imagine H2O, a nonprofit that supports start-ups to develop and deploy their technologies and solutions to solve global water issues.

Doromal estimated companies can save 20 to 30% over traditional removal and capping methods, with the number increasing as the company gains economies of scale.

"We know at the end of the day, companies make decisions based off dollars and cents. Eliminating their environmental liabilities protects shareholder value," he said. "We are also eliminating the liabilities and threats to human and environmental health."

Albino added that the company is actively working with numerous organizations to build community awareness about the contamination. The cofounders credited NASA for the unique opportunity the technology presents. As a former NASA contractor, Albino is also using the expertise he gained working in NASA's innovative environment.

"Society is more in tune with the environment and has finally learned what NASA has been operating on since the '60s – that anything you send into space has to be sustainable, because, for example, whatever you're going to emit, you're going to have to breathe in," he said. "Whatever we do on Earth has to be sustainable, too."

Quinn agreed and was pleased to see this unique technology finding its way into environmental remediation efforts.

"I have these really cool pictures of footprints on the Moon hanging in my office," she said. "I would like to have a footprint-legacy behind us that's positively impacting Earth." ●

NASA field-tested the Sorbent Polymer Extraction and Remediation System (SPEARS) in a contaminated pond in Altavista, Virginia, after lab experiments successfully removed polychlorinated biphenyls (PCBs) from a liquid environment. Several of these tests proved that a commercial product could be developed to remove PCBs from waterways, reducing the toxins entering the food chain. *Credit: Gagan Cambow, ecoSPEARS*

Space-Age Water Conservation

NASA's need to conserve water in space has long supported terrestrial water-purification techniques

The more difficult a problem is for NASA, the more solutions it eventually produces for the rest of us.

Few challenges are more pressing for the space agency than the need for clean water. Water is heavy – much heavier than the liquid hydrogen and oxygen NASA uses for rocket fuel – and every pound launched into space costs thousands of dollars. So on the space station, nothing is wasted – sweat, urine, and even breath moisture are collected, purified, and recycled as drinking water. But despite its origins, the water astronauts drink is cleaner than what's available to most people on Earth.

To achieve this, NASA has pushed the cutting edge of water purification since the agency's early years. And most of these innovations have found plenty of use here on the ground, too, in homes and water bottles, in industrial settings, and in remote locations where safe drinking water is scarce. As the worldwide demand for fresh water grows, this technology becomes more essential every day, as it ensures that people have enough safe water to drink, treats polluted water, and eases the demand on natural aquifers.

These are just a few examples of NASA technology now cleaning water on Earth.

Shower like a Martian

In one recent development, an unlikely partnership between NASA and a Swedish university – with the help of filter technology the space agency helped develop almost 20 years ago – led to the world's first water-recycling shower.

In 2012, Mehrdad Mahdjoubi, then a master's student in industrial design at Lund University in Sweden, traveled to NASA's Johnson Space Center in Houston as part of an annual program to learn about the challenges of designing habitats for astronauts. The focus was on a five-year Mars stay.

Current astronauts, short on water and gravity, take sponge baths, but Mahdjoubi thought spacefarers with feet planted on Martian ground would prefer a real shower. But water on Mars' desert surface is still scarce, so Mahdjoubi came up with an idea for reusing the flow. "I'd have never thought about doing something like this if I didn't have that NASA experience," he said.

To rapidly purify and reuse water, he hit on an especially thorough water filtration technology developed in part with NASA funding, known as NanoCeram (*Spinoff* 2004, 2009, 2013, 2017).

Inspired by a NASA design exercise, a Swedish inventor used filter material developed with help from NASA to create the first recirculating shower, saving water and energy.

Water is one of Earth's most precious resources. For many years, technology invented or supported by NASA for life-support systems in space has been used to both clean and conserve water on the blue planet. *Credit: DieterMeyrl via Getty Images*

Orbital Systems' Oas shower is the world's first water-recirculating shower. It was inspired by a university's partnership with NASA and is enabled by a filter technology NASA helped fund with an eye toward improving astronaut life-support systems. *Credit: Orbital Systems*

Other filters have micropores tiny enough to physically filter out bacteria and even viruses, but these are painfully slow. A material invented by Argonide Corporation, however, made up of positively charged microscopic alumina fibers, can remove virtually all contaminants, including bacteria and viruses, despite having significantly larger pores – allowing a much higher flow rate. The positive charge of the fibers attracts and traps microorganisms and other contaminants, which generally carry a negative charge. Activated carbon in the filter aids in snaring particulate, chemical, and soluble contaminants.

Under two Small Business Innovation Research contracts from Johnson in the early 2000s, Argonide optimized its nanofibers for strength and virus adhesion and built, tested, and validated full-scale filter models. Since then, other companies have used the filters in water bottles, portable humanitarian units, and industrial water purification. And now Mahdjoubi has incorporated the filter into a recirculating shower known as Oas – Swedish for "oasis" – built and marketed by his new company, Orbital Systems.

The shower starts with less than a gallon of water and circulates it at a rate of three to four gallons per minute, more flow than most conventional showers provide. The system checks water quality 20 times per second, and the most highly polluted water, such as shampoo rinse, is jettisoned and replaced. The rest goes through the NanoCeram filter and then is bombarded with ultraviolet light before being recirculated. The Swedish Institute for Communicable Disease Control has verified that the recycled water is cleaner than tap water.

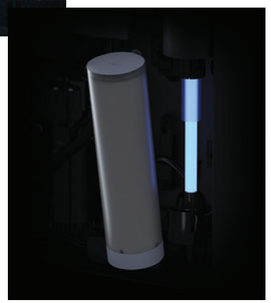
And because the reused water is already warm, it takes minimal energy to heat it back to the target temperature.

"There's a general assumption you can't do anything about water conservation without compromising your life quality," said Mahdjoubi. "But we don't tell people to stop showering, and we don't destroy their experience. We enhance it with a higher flow rate. The ability to save without sacrifice, I think, is the most important part of our value proposition."

Orbital Systems, headquartered in Sweden with U.S. offices in Sausalito, California, has raised about $50 million in investments and employs 60 to 70 people.

The company has sold several thousand units, so far mostly to hotel chains and real estate developers, and the showers are becoming available to individual consumers in Sweden, Denmark, and Germany this year. Mahdjoubi plans to expand to North America, Asia, and beyond but first needs to enlist distributors and certify installers. In the longer term, he wants to enable an entire habitat that runs on closed loops, recycling as much and using as little water as possible, just as a Martian habitat would.

"As humans, we're really good at innovating, but we tend to be quite complacent until we actually have to do it," Mahdjoubi said. "Designing for Mars forces more creativity."



The combination of a NanoCeram filter, left, and an ultraviolet light lets the Oas shower purify and recycle all but the dirtiest water. *Credit: Orbital Systems*

Ancient Technology Enters the Space Age

Likewise, NASA engineers had to get creative as soon as the Apollo missions required a long-term water supply. One technique they explored in those early days was the use of silver ions to neutralize bacteria and viruses.

Even then, the concept was not new. Silver has been used to preserve and purify food and beverages since ancient times, but scientists are still researching the best and safest ways to deploy the technique.

The ancients, of course, had no idea how it worked – that when positively charged silver ions dissolve into water or other substances, they bond with and disrupt the negatively charged cell membranes of bacteria and other microorganisms before entering them and wreaking general havoc. But as understanding has improved, so has technology for delivering the ions.

In the 1960s, Johnson, then known as the Manned Spacecraft Center, commissioned an electrolytic silver ion generator to purify water on the Apollo missions. The following decade, in the run-up to the space shuttle missions, the center sponsored a more advanced prototype.

The silver ion-based purifiers never flew on NASA missions, but here on Earth, they've given rise to filter systems for home faucets, pools, spas, boilers, hospitals, and more.

One product family with perhaps the most enduring success didn't even get the technology directly from NASA.

In the 1970s, Arizona inventor Ray Ward requested a technical information package from NASA based on the silver ion system built for the shuttle, which he used to build a prototype tap-water filter. Ward went on to found the Bon Del and Ambassador lines of water filters, which became a $50 million-a-year business (*Spinoff* 1982, 1987, 1992). Along the way he also got some help from water treatment company Ionics Inc.

After helping another company implement silver-ion water purification technology from the space shuttle, Puronics has incorporated its SilverShield version into whole-house water conditioners to prevent bacterial growth in filters.

The Puronics Defender whole-house water conditioner uses silver-ion technology based on work NASA did in the run-ups to the Apollo and space shuttle missions. Positively charged silver ions neutralize bacteria in the unit's filter beds. *Credit: Advanced Cascade Water Systems Inc.*

That company, now known as Puronics Water Systems Inc., later used the NASA technology Ward had introduced it to as a starting point for a water softener that wouldn't breed bacteria (*Spinoff* 1991).

Today Puronics, headquartered in Livermore, California, sells several lines of whole-house units incorporating the technology, which it calls SilverShield, each with different features and price points. Silver particles in the devices' filter beds prevent them from breeding bacteria.

CEO Scott Batiste said the home units with SilverShield remain the company's core products, accounting for about 70 percent of its overall business, and the product line has been doing 15 to 20 percent more business each year lately.

"I think it's a real testament to this technology that we've been using it since the late '80s, early '90s, and it's still a growing product line," he said. "I think NASA should be proud of that, and of course we're excited about it."

Carbon impregnated with silver ions forms the filter bed for most of Puronics' product lines. *Credit: Puronics Water System Inc.*

Using Nature's R&D Lab

One of the most remarkable – and possibly most effective – water-treatment technologies NASA has explored is a membrane embedded with the same natural proteins that transport water through the membranes of living cells (*Spinoff* 2019). Known as aquaporins, these proteins are what allow plant roots to absorb water from soil and human kidneys to filter about 45 gallons of blood per day. They can transport water through cell membranes one molecule at a time, while rejecting other substances.

Now companies all over the world are looking at various ways these membranes can be used, including many pilot wastewater treatment projects, whether adding efficiency to existing wastewater treatment facilities or purifying wastewater that until now has gone untreated, polluting groundwater and waterways.

The concept has been pioneered by Danish company Aquaporin A/S, and when NASA's Ames Research Center in Silicon Valley, California, learned what the company was trying to do in 2007, the center became the first paying customer. Ames and the European Space Agency tested the membranes on flights to the International Space Station.

In 2016, Aquaporin delivered its first commercial product, an under-sink filter module for home use.

These operate through reverse osmosis, using pressure to push water through the filters. But the company had even bigger plans for the membranes in forward osmosis, a process that drives itself without any outside influence. With saltwater on one side of the membrane and wastewater on the other, thermodynamics compel the salt to distribute itself evenly throughout all the water in the system. But because salt can't pass through the membrane, it draws the fresh water through from the other side, leaving only waste.

While forward osmosis is an old technique, the aquaporin proteins' extremely high selectivity for water molecules gives Aquaporin A/S an advantage. "We have the highest rejection rates and the lowest reverse salt flux rates in the market," said CEO Peter Holme Jensen. "This is why we can do stuff in forward osmosis that others can't – because we extract water, and other forward-osmosis technologies extract water and a bit of something else."

The company, based outside of Copenhagen, has now partnered with companies and other entities around the world on pilot projects or lab tests to

In the gray water reclamation system at Ames Research Center's Sustainability Base, the two beige Aquaporin HFFO14 forward-osmosis modules on the left have as much filtration capacity as the entire legacy system on the right. *Credit: Aquaporin A/S*

try the membranes in almost 60 different forward-osmosis applications. About half of those projects are treating wastewater generated by a range of sources, from landfills to olive oil production to bus depot washing.

One of those is back at Ames, where NASA's Sustainability Base, one of the federal government's most environmentally friendly buildings, is trying out Aquaporin HFFO14 forward-osmosis modules for treating gray water – wastewater from sinks, drinking fountains, and other non-sewage sources. This pilot has been running since fall of 2019 and requires less energy and maintenance than the building's previously existing gray water reclamation system while taking up far less space.

In one of the larger wastewater treatment pilots, Canadian start-up Forward Water Technologies opened a demonstration plant in Alberta last year, using Aquaporin filters to treat water hauled in from oil and gas drilling sites, among other industries.

But Aquaporin is taking particular aim at textile companies, which generate large amounts of highly concentrated wastewater. Most of these are in Asia, where many companies currently don't treat their wastewater, leading to widespread pollution. Both consumer demand and "zero liquid discharge" requirements some governments are putting in place are changing that, so Aquaporin is supplying filters to Gradiant Corporation, a company that specializes in sustainable water treatment, for use in Asian textile mills. "We have a specific focus on the textile industry because consumers are asking for it," said Holme Jensen.

Meanwhile, other businesses that do treat wastewater tend to be slow to adopt new technology. "Water companies take nine to 13 years to adapt to new innovations. If we waited for them, we would go bankrupt," says Holme Jensen.

But his company has found that some other industries – specifically the food and beverage industry and the field of hemodialysis – are more open to new ideas.

By extracting water in a cold concentration process that uses forward osmosis, companies can increase the alcohol content of beer, create highly concentrated foods, or turn semisolid foods into durable solids. Other techniques work but can change the flavor and texture. "When you do this with forward osmosis, you do it in the gentlest way possible, gently extracting water at room temperature," Holme Jensen explained.

Between 20 and 30 food and beverage companies – many of them household names – are now running pilots with the company's forward-osmosis modules, he noted, often with the goal of creating their own patented new products. "For us it was a little surprising."

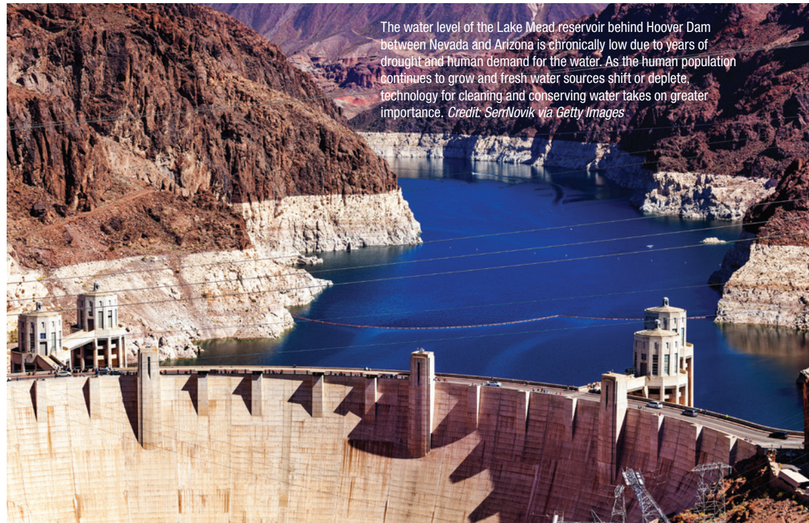
With early NASA funding and testing, a company incorporated nature's water-filtering proteins into membranes. Now companies and researchers are trying them out for many applications, from wastewater treatment to dialysis.

And in healthcare, forward osmosis has the potential to make dialysis portable, improving patients' quality of life, he said. Dialysis patients often spend hours traveling to and from treatment three or four times a week, where they spend another three or four hours bedridden, creating a sedentary lifestyle.

This is partly because hemodialysis is a massive water consumer. The process requires about 200 liters of water per treatment – all of which ends up as wastewater. If clean water were extracted from the waste and reused throughout the treatment, he said, dialysis could fit in a backpack.

"We're testing forward osmosis in a closed water-recycling loop with a lot of players in dialysis," Holme Jensen said. "Medical device companies understand and pick up on the technology because if you look at how a kidney works, it reuses water in a closed loop."

And after all, the mechanism that makes that closed loop work is the aquaporin protein. ●



The water level of the Lake Mead reservoir behind Hoover Dam between Nevada and Arizona is chronically low due to years of drought and human demand for the water. As the human population continues to grow and fresh water sources shift or deplete, technology for cleaning and conserving water takes on greater importance. *Credit: SerrNovik via Getty Images*

In Cloud Computing, Open Source Becomes Big Business

OpenStack, co-created by NASA, gained a huge user base and gave rise to other open source cloud computing tools

Telecommunications providers are the biggest users of Red Hat's enterprise version of OpenStack, but it's also widely used in healthcare, manufacturing, banking, and any other industry that uses cloud computing. *Credit: sharply_done via Getty Images*

Open source software, once the playpen of renegade hackers and hobbyists, had already gone mainstream. Cloud computing was newer and less defined but already commercially available. In 2010, a small team of engineers at NASA's Ames Research Center in Silicon Valley, California, brought the two neatly together.

The result, a collaboration between NASA and Rackspace Inc., was called OpenStack. Since its release that July, open source cloud computing has steadily gained popularity, with many of the world's largest companies making the switch.

"That original work has expanded across most industries, because it solved a general problem and opened that solution up to let people expand on it," said Brian Gracely, senior director of product strategy at Red Hat Inc., based in Raleigh, North Carolina. Red Hat became the first company to achieve major success marketing its own version of OpenStack and subsequent open source cloud computing products, and it remains the biggest player in that field.

Outsourcing to the Masses

The general problem the Ames team set out to solve was to find a way for computing power and storage to automatically scale up and down according to the needs of individual projects and users across a large number of virtual servers. This is the essential definition of cloud computing, or infrastructure as a service. They called the project Nebula.

Such systems already existed, with Amazon Web Services' Elastic Compute Cloud as the prime example, but they were proprietary, used on a privately owned cloud where subscribers bought space. The team at Ames wanted NASA to be able to host and manage its own computing and data.

> NASA co-created the first open source cloud infrastructure, OpenStack, which companies have commercialized and built upon with other open source tools like the OpenShift platform. Open source cloud computing subsequently exploded across industries.

"NASA didn't have the staff to build the whole thing and maintain it long-term," said Gracely. "It's a problem a lot of companies had too."

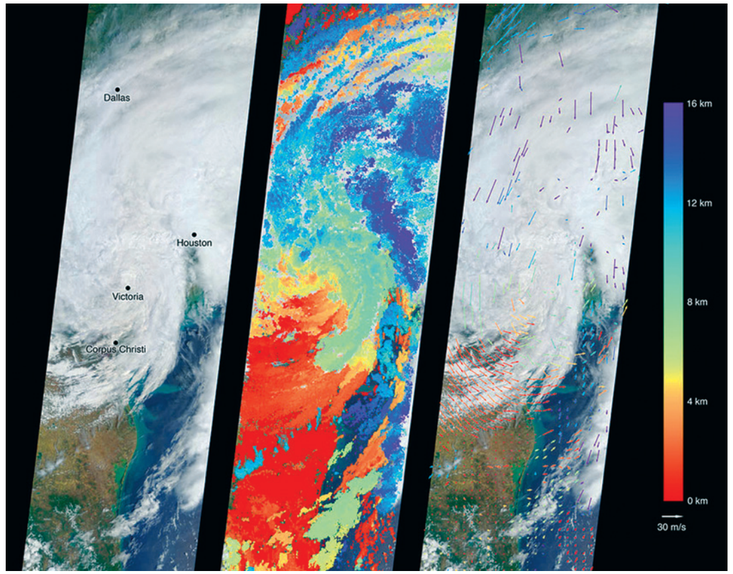
NASA decided to take the open source route, developing the code online in the public eye, where any other programmers can contribute and no one owns the code.

After a few years of false starts and on-and-off work, the team decided to create its own "fabric controller," the brains that would manage computing, storage, and networking. The result was called Nova.

"Launched NOVA," one of the NASA contractors wrote in a blog post, noting that the code was open source. "It's live, it's buggy, it's beta. Check it out."

When engineers at the cloud computing company Rackspace did just that, they recognized a code that took the same approach they'd been working on. The two groups teamed up and, less than two months later, announced the release of OpenStack (*Spinoff* 2012, 2016).

"The best, most flexible software gets built in the open source community," said Gracely, noting that this is also Red Hat's development process. "If I have a common problem, we can bring all our engineering talents together and solve it at a lower cost to everyone. If you have a unique aspect to your problem, you can tweak the code to your need, and now others with your need can use it."



The Atmospheric Science Data Center at Langley Research Center houses five to six petabytes of data, such as these images showing the cloud heights and wind speeds of Tropical Storm Harvey shortly after it was downgraded from a hurricane. The center is working to take advantage of the OpenShift platform's ability to make its applications automated and portable to any computing environment. *Credit: NASA*

Red Hat's free version of OpenStack, known as Red Hat Distribution of OpenStack or RDO, launched in 2013 and has proven popular, especially among major nonprofits and research institutions. Perhaps the most famous use case is at CERN. The European nuclear research facility uses RDO to run calculations on the 100,000-core computer cluster for the Large Hadron Collider that made the first observations of a long-theorized particle called the Higgs boson.

Red Hat is a business, however, and also needs to make money on its software.

"We have an open source development model and an enterprise software business model," Gracely explained. In other words, the basic software is developed in an open source environment and available for free, but customers of Red Hat's commercial OpenStack offering receive technical support, updates, upgrades, and fixes, among other benefits. And like other enterprise software, it's geared toward highly secure, large-scale, long-term use.

Automation for Applications

During the initial development of OpenStack, the Ames team also made an attempt at creating a sort of second layer of code – an automated platform for building and deploying applications on a cloud infrastructure, Gracely said. "But it's very hard for infrastructure people who don't create applications to solve problems for an applications team." The aborted attempt signaled a need that the market could fill, he said. Less than a year after OpenStack's launch, Red Hat released its first version of OpenShift to help fill that niche.

Rather than infrastructure as a service, OpenShift is what's known as a platform as a service, a set of tools for developing and maintaining cloud applications. As such, its main job is to orchestrate application containers – standardized self-contained units that hold all the code and software an application needs to run in the cloud.

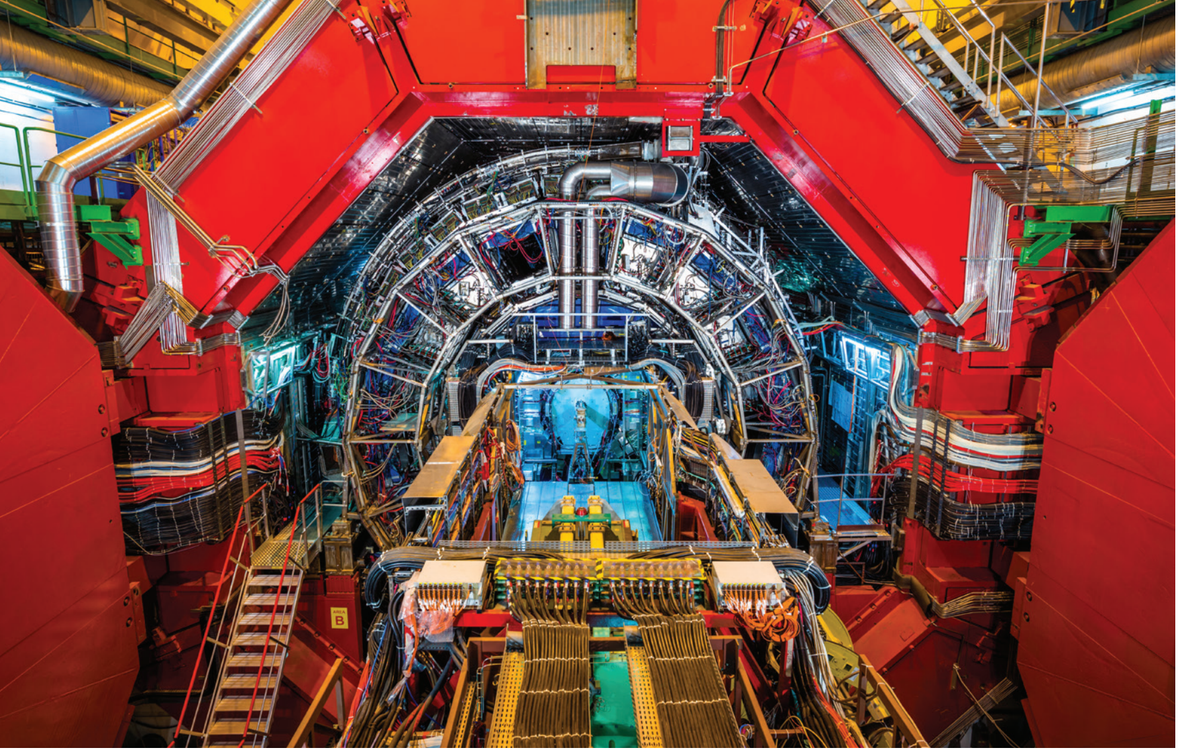
Gracely described OpenShift as "a sort of second generation" that arose to take better advantage of cloud software like OpenStack.

"Previously, a developer wrote an application and then had to think about how it talks to the network, how it talks to the storage system and database, how to make sure it can scale to more users, how to make it highly available, for example if a server dies," he said. OpenShift automates these tasks. "Give it your application, tell it how you want it to run, and it takes care of all those complexities."

OpenShift can be – and often is – run on an OpenStack cloud, but it can be used in any computing environment. It also builds on OpenStack in more direct ways. For example, while it doesn't use the NASA-invented Nova component that still handles computing at the heart of OpenStack, it does incorporate other OpenStack components that descended from Nova. These are the Cinder block storage service, Neutron for networking between interface devices, and Ironic, which provisions individual physical servers, rather than virtual servers.

"By migrating to OpenShift, we are preparing our applications to be highly portable and run in any number of possible environments."

Jeff Walter, Langley Research Center



The European nuclear research facility CERN uses the free, open source Red Hat Distribution of OpenStack to run calculations for the Large Hadron Collider that made the first observations of the Higgs boson. *Credit: xenotar via Getty Images*

Back at You, NASA

NASA's Langley Research Center in Hampton, Virginia, is now an OpenShift customer, as the secondary benefits of Ames' work a decade ago continue to reverberate through the space agency.

The Atmospheric Science Data Center (ASDC) at Langley is working to restructure its applications and services to run on the OpenShift platform. "We're trying to think about how we can be more ready to reap the benefits of cloud technology to be more flexible and agile," said Jeff Walter, systems architecture lead at ASDC.

The center houses five to six petabytes of data on local storage arrays and is preparing to migrate some of its data to the Amazon Web Services cloud. But Walter said it's not the volume of data that's driving a proposed switch to a local OpenShift cloud platform, so much as a desire to improve efficiency and prepare for the future.

Currently, one project might have a server running at capacity while another server sits idle, he explained. "It would be nice for the first project to be able to use some of the other project's hardware." Virtual servers would be able to operate across physical servers or coexist on a single machine. And OpenShift's automation would eliminate work and human error. "It's about having a centralized environment that allows developers to think about an application and how it's structured from a business point of view and not worry about how and where this thing is going to run," Walter said.

"By migrating to OpenShift, we are preparing our applications to be highly portable and run in any number of possible environments, including on-premises or in any major commercial cloud with little or no rework," he added.

The group is also weighing whether it might run OpenShift on an OpenStack infrastructure.

Meanwhile, the Jet Propulsion Laboratory has been using Red Hat's OpenStack Platform in its on-site cloud since 2016.

Today, the World

Red Hat's free version of OpenStack now has well over 100,000 community members and is supported by about 700 companies in 185 countries. Meanwhile, Red Hat remains the world's largest distributor of enterprise OpenStack, and more than half of the company's OpenStack customers use it in conjunction with OpenShift.

"We have OpenStack customers in every sector in the cloud computing industry," said Nick Barcet, Red Hat's senior director of technology strategy. "Telecom providers have the largest share of the deployments, but from healthcare to manufacturing, OpenStack is delivering value in a very wide variety of cases."

By May of 2019, more than 1,000 customers were using Red Hat's enterprise OpenShift Container Platform, including almost half of Fortune's Top 100 companies.

In 2012, Red Hat became the first open source software company to take in more than a billion dollars in a year. In February of 2019, a few months before IBM acquired the company, it reported total revenue for the previous fiscal year of $3.4 billion. IBM bought Red Hat for exactly 10 times that amount. By then, the company employed more than 14,000 people in offices across the United States and around the globe.

Red Hat was thriving before OpenStack opened up cloud-building to the masses, but the company is one of many that have benefited from that shift, with most of its products now built around open source cloud computing. "At the time of that NASA work, it was really unique," said Gracely. "We're thankful they did it, and we're thankful they've remained a partner and a customer today." ●

"The best, most flexible software gets built in the open source community."

Brian Gracely, Red Hat Inc.

Among the industries where open source cloud computing has become popular since NASA introduced the concept in 2010 is healthcare, which requires the secure management of vast amounts of data. *Credit: SDI Productions via Getty Images*

A Case Made in Space

NASA investment in small businesses helps both thrive

It's as true in tech as it is in ancient fables: the little guys can get things done. A dehydrated gel to keep your drinks cool, a cooling system for supercomputers, and a polymer for medical implants – through the Small Business Innovation Research Program, NASA-backed technology is seeing new life.

SBIR contracts, and later their Small Business Technology Transfer (STTR) contract cousins, began in the 1980s as a project of the Small Business Administration, promoting the development of cutting-edge technologies to benefit both government agencies and private industry. This annual, multi-phase research funding enables small companies to develop technology that's of interest to NASA – and the companies can then use what they learn to develop products with wide-ranging benefits.

The agency selects technologies that have potential commercial and government applications, but many require more time, investment, and development than would allow private investors to realize returns. Sometimes it can take years of research and development, and some projects may never materialize. But as these examples show, technologies that undergo risk-reduction and products that are developed with SBIR funding can also eventually become hugely profitable as well as advance NASA missions and research.

From Supersonic Jets to Medical Tech

In the 1990s, NASA was researching ways to move people and cargo at extreme speeds. While supersonic airliners like the Concorde were around back then, tickets were very expensive. NASA's High-Speed Civil Transport research program looked to bring such high-speed travel to the mainstream.

Robert Bryant, an engineer at NASA's Langley Research Center in Hampton, Virginia, explored materials for building more durable aircraft composites and adhesives. These polymer composites would be able to withstand the stresses of sustained supersonic air travel for much longer than traditional materials. Imitec, a small materials manufacturing firm in Schenectady, New York, received SBIR contracts to produce samples of the NASA resins and realized that, with modifications, their durability could be useful in other areas.

"The Langley work was developed for composites and adhesives," Bryant said. "And there were some aspects of the NASA resin chemistry that would allow the polymer to be used in other technologies."

NASA SBIR funding to research resilient materials for supersonic airplanes helped to create a new kind of polymer. This material caught the eye of a medical technology company, which is now trying it out in more durable medical implants.

Hip replacements are typically made of metal and polymer composites. Imitec used the knowledge gained from NASA SBIR research to develop a new, more durable polymer material that's being tested in these specialized implants. *Credit: Rike via Getty Images*

When visiting Langley, an Israeli medical company named MMA Tech saw potential in the polymers for hip replacements. If the material could withstand the environmental stresses from aerodynamic forces in jet aircraft, similar formulations could be just as good at resisting wear from joints in the human body. Imitec's two phases of SBIR research helped pave the way for a new polymer called MP1. Like the other NASA polymers, MP1 was durable and wouldn't interact with the body, which made it ideal for use in medical implements. With a supplier guaranteed, MMA Tech contracted with Imitec to obtain MP1 for its research.

Jack Keating, president of Imitec, said the trials of MP1 implants in Israel sparked further interest. MP1 hip replacements have been implanted into patients in New Zealand, and research found that the polymer's chemical makeup makes it especially safe for implantation because it resists viral and bacterial growth. Keating said further research is being done to determine if the material could be used in widespread medical implants.

In the 1990s, Langley Research Center was looking for polymers to make building and operating supersonic airliners more viable. Now, a derivation from that materials research called MP1 is being tested in hip replacements. *Credit: NASA*

Fiber Optics Feel the Heat

NASA's work with materials science doesn't end with airplanes. Thermal protection systems are vital to protect spacecraft and astronauts from the incredible heat that builds up during atmospheric entry. Without heat shields, rovers couldn't land on Mars, and astronauts couldn't return safely from the International Space Station. The important job of testing these shields and ensuring they stay strong and functional is the responsibility of scientists at NASA's Ames Research Center in California's Silicon Valley.

In durability testing at the Ames Arc Jet Complex, temperature sensors called thermocouples are embedded in the heat shields. While durable, these instruments can only measure temperatures in specific parts of the shield and are highly susceptible to electromagnetic interference. Researchers wanted to get more information and turned to the SBIR program for solutions.

Intelligent Fiber Optic Systems (IFOS) Corporation of San Jose, California, has been working on high-precision temperature and pressure sensor systems for more than 20 years with the help of SBIR funding from NASA and other agencies (*Spinoff* 2002, 2020). As its name suggests, IFOS deals in fiber optics – thin strands of glass that use light to transmit data. Fiber optics present more opportunities for distributed data collection than traditional temperature sensors made from metal, in particular because "you can take measurements at different locations than where thermocouple wires are located," said Ethiraj Venkatapathy, senior researcher for entry systems at Ames.

IFOS's sensors are special micro-holograms etched into thin strands of glass wire. These holograms, known as fiber Bragg gratings, reflect light differently based on the temperature and strain in the surrounding area. When light is guided through the fiber optic cabling, a specialized computer can read the levels and spectral wavelengths of the reflected light to provide real-time temperature readings at the locations of the micro-holograms distributed along the fiber.

An Intelligent Fiber Optic Systems (IFOS) Multi-Channel Interrogator takes readings from micro-holograms etched into optical fibers and translates it into data. *Credit: Intelligent Fiber Optic Systems Corporation*

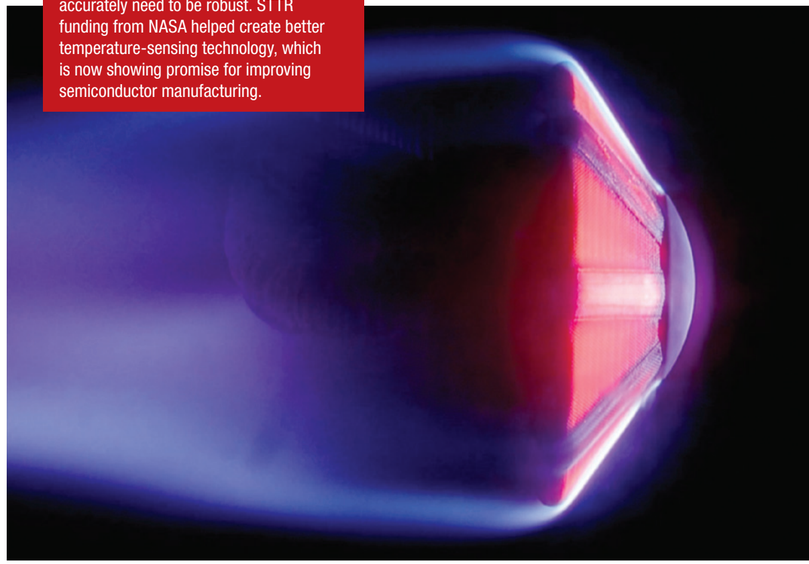
Because the system is based on glass fibers, rather than metal, it's also immune to electromagnetic interference.

Two 2010 STTR contracts from Ames funded the development of special, high-temperature versions of these sensors for heat shield testing and tested them up to more than 3,200 degrees Fahrenheit. The sensors were able to read temperature changes more quickly than thermocouple-based sensors, and they allowed all electrical wires to be replaced with a single optical fiber, said IFOS's Chief Scientist Richard Black.

IFOS has now sold a product based on this technology to a major U.S. semiconductor equipment manufacturer that's exploring how these high-temperature sensors can improve its manufacturing processes and reduce factory downtime. Semiconductor construction requires extreme precision, such as heating tiny points across silicon wafers. IFOS President and Chief Commercial Officer Mehrdad Moslehi said the company's heat-sensing technology could be a game-changer for such production tools and processes, ensuring the necessary equipment operates reliably and enabling intelligent preventive maintenance and equipment diagnostics.

"Our solution will enable our semiconductor manufacturing customer to achieve enhanced equipment uptime, reduced cost of ownership, and improved manufacturing process control," said Behzad Moslehi, CEO of IFOS.

Spacecraft heat shields need to withstand incredible temperatures during atmospheric entry, and sensors to test these systems accurately need to be robust. STTR funding from NASA helped create better temperature-sensing technology, which is now showing promise for improving semiconductor manufacturing.



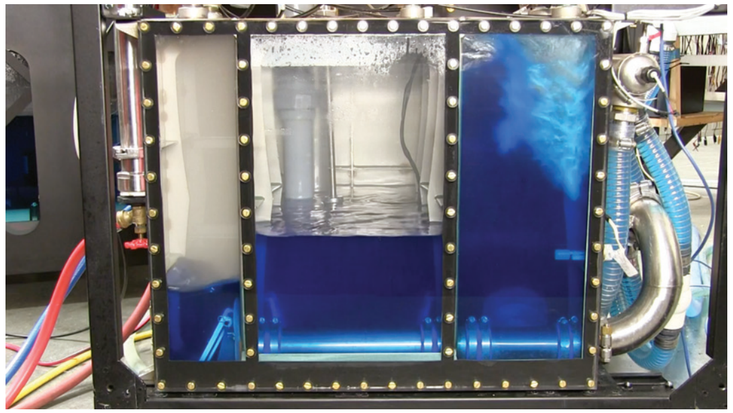
IFOS's fiber optic thermal sensors were designed to be embedded in heat shields for testing at the Ames Arc Jet Facility (pictured), but their extreme heat resistance makes them perfect for use in semiconductor manufacturing. *Credit: NASA Ames Video Group*

Engine Pump Helps Computers Chill Out

Ensuring that sensitive equipment is the right temperature is important when working with high heat, but sometimes you have to keep things cool, such as computers in a data center. Now a technology originally invented for spacecraft engines is doing just that.

One of the most important elements of rocket design is ensuring that fuel is constantly flowing to the engines. Most of the pumps that do this use a whirring piece of metal to push fuel from one tank into another, but Steve Harrington, president of Flometrics, designed a pump that didn't have any moving parts at all. His "pneumatic ejector" uses pressure to push the fuel from one chamber to the next, and then out of the pump.

During the late 2000s, NASA was looking for a fuel pump to use in control thrusters for both a lunar landing module and small satellite launch rockets, so Flometrics applied for an SBIR contract with NASA's Glenn Research Center in Cleveland to complete its fuel pump research.



This demonstration of the Chilldyne cooling system pumps coolant from three chambers into adjacent servers. Changes in pressure between the chambers cause fluids to flow through the loop. *Credit: Flometrics*

"They had a very interesting approach to developing technology," said Steve Schneider, the former NASA project lead.

By the end of Flometrics' Phase I SBIR contract, the company's pump could cycle two gallons of liquid nitrogen per minute through a test loop. The pump showed promise for the launch vehicle application, as it was far lighter and more reliable than other designs NASA was considering at the time. And while the research ultimately did not produce a rocket, the project would soon take a different turn, into keeping computers cool.

When NASA wanted a lighter, more reliable rocket pump, it awarded SBIR funding to a fluid dynamics specialist to develop one. While the resulting pump didn't find its way into a space rocket, it soon became the starting point for a liquid cooling system for supercomputers and servers.

The Flometrics Fuel Pump hooked up to an Atlas Vernier thruster in 2018. *Credit: Flometrics*

"Half the energy that goes into a data center is for air conditioning. That means data centers are 50% efficient, only half the energy goes into the computers. If planes were like that, we'd have to land in Hawaii every time we flew to Japan," Harrington said. "That offended my thermodynamic sensibilities, so I came up with a liquid computer cooling system."

Flometrics soon received another SBIR contract from the Defense Advanced Research Projects Agency to address these new applications, and the efforts were spun off into another company, Chilldyne of Carlsbad, California. Chilldyne's design traces its lineage back to that original fuel pump proposal, only instead of rocket fuel flowing to powerful engines, coolant is pumped across the processors of large computer hardware.

Harrington said the original NASA SBIR work proved that a multi-chamber pump like this could be scalable, and the pump has clear benefits for any large computing center. With liquid cooling the processors directly, and without any moving pieces of hardware, electricity costs can be pushed way down. Tests at the Department of Energy with a similar system saw power use drop by just over 20%. As of 2020, Chilldyne has 18 full-scale cooling systems installed at three massive data centers, including some at Sandia National Laboratories.

Cooling Rocket Fuel and Drinks Alike

Maintaining the right temperature is important for applications both on Earth and in space, but not all SBIR research ends up in aerospace or computing. Sometimes it's just to make a nice drink.

Aerogel was first created in the 1930s. When the liquid component in a gel substance is replaced with air, the material gains incredible insulating properties while becoming nearly weightless. NASA has researched aerogels for various purposes, ranging from sample collectors to protecting Mars rovers from the elements.

Under SBIR contracts from NASA's Kennedy Space Center in Florida in the 1990s, a company developed the first practical aerogels in the form of durable, flexible blankets to keep rocket fuels cool. Aerogels have been spinning off into myriad commercial applications ever since (*Spinoff* 1998, 2001, 2008, 2010, 2018, 2020).

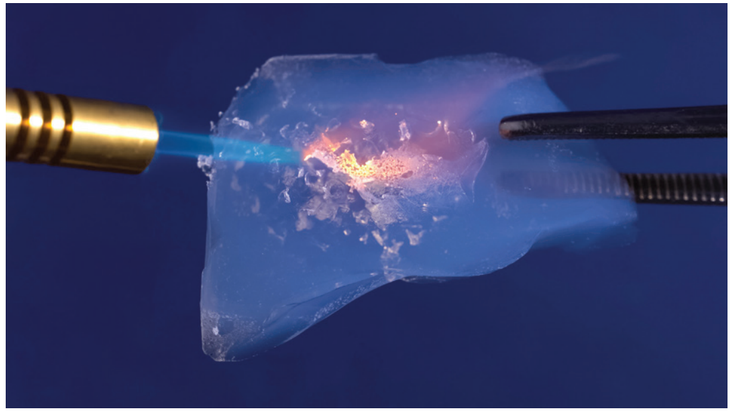
Now outdoor equipment company CamelBak, headquartered in Petaluma, California, is using aerogel from that same company for a different kind of insulation. Instead of keeping rocket fuels in liquid form, the Podium Ice water bottle keeps liquids at a stable temperature for hours.

"Our thinking was, what's the best passive insulation possible so a bicyclist can get the best bottle possible?" said Derek Campbell, senior director of product development at CamelBak. Because of this stability, CamelBak hopes to include the aerogel design in a wider range of water bottles, including ones built to military specifications.

Starting with a comparatively small investment of $500,000, aerogel now generates millions of dollars in annual revenues and is disrupting industries.

It, like the other examples in this story, shows how small businesses can make amazing technologies for NASA that have even further-reaching benefits for the rest of us. Research for rocket plumbing resulted in computer coolers, materials for supersonic aircraft can help people walk, and even your water bottle could have some aerospace tech. For companies looking for a boost, the SBIR program could be their ticket to the stars. ●

Aerogels are the world's best insulators, but it took SBIR funding from NASA to turn them into something usable. Now they're appearing in all kinds of applications, including a water bottle that keeps drinks hot or cold.



Aerogels are the lightest solid known to man, and one of the greatest insulators, but it took NASA investment to develop a form that was easy to use. Now it's used extensively in aerospace, as well as in consumer goods. *Credit: LYagovy via Getty Images*

CamelBak's Podium Ice bottle uses flexible aerogel insulation to keep water cool. *Credit: CamelBak*

Gecko Gripper Finally Sticks

After two decades of effort, gripper imitating a gecko's toe pads outfits industrial robots

NASA was interested in the technology for astronaut mobility and grappling satellites in orbit. A former JPL researcher licensed it and received NASA SBIR funding to develop it for industrial grippers, which are now going into factories.

"Moving around in microgravity is more of a climbing problem than a walking problem."

Aaron Parness, formerly of JPL

No sooner had the gecko's secret been cracked than humans got to work trying to copy it.

"It was one of those mysteries that had been around for a long time," said Aaron Parness, who until recently managed the Robotic Climbers and Grippers group at NASA's Jet Propulsion Laboratory in Silicon Valley, California.

Aristotle was the first to go on the record asking how the gecko is able to scurry up and down surfaces in open defiance of gravity, but anyone watching a six-inch lizard cross a ceiling would have to wonder. The Greek philosopher's question wasn't answered until about 20 years ago, in part because the secret lay in a force of physics discovered millennia after Aristotle's death.

Van der Waals forces are weak electrostatic attractions between polarizable molecules.

Geckos' toepads take advantage of this slight attraction by multiplying it. Each pad has about half a million hairs, made of keratin like human hair but much thinner. Each of these setae ends with hundreds of far thinner nanohairs, creating an incredible amount of surface area that, with minimal pressure, completely conforms to the tiniest features of any surface it touches. It's enough surface-to-surface contact that van der Waals forces become significant.

The concept is simple, but recreating such a surface is not.

From Spacewalks to Circuit Boards

When Parness arrived at JPL in 2010, a decade after scientists had unlocked the gecko's mystery, he had already been working on gecko-like human climbing technology as a graduate student at Stanford University. (Spider-Man gloves are still in the prototype stage.)

NASA was interested in such gripping technology for space operations. "Moving around in microgravity is more of a climbing problem than a walking problem," he said, noting that gecko-like pads would be easy to use and radiation-resistant, and they wouldn't rely on suction cups or other vacuum technology that's useless in a vacuum.

A gecko's toepads have millions of microscopic hairs that capitalize on a weak electrical attraction known as van der Waals force to let the lizard scale even the smoothest surfaces. It's a simple concept but difficult to reproduce. *Credit: David Clements*

Engineers at the Jet Propulsion Laboratory (JPL) spent years working with a team at Stanford University to develop grippers that could imitate the toe pads that let geckos defy gravity. *Credit: Tim Vickers*

By the time Nick Wettels joined Parness' group as a post-doctoral researcher in 2013, the work had turned to grappling satellites for repair in orbit. Wettels is now director of research and development at OnRobot, the first company to offer a commercial robotic gripper based on the gecko toe pad. At the time, he was leading the company Perception Robotics, which he had recently cofounded.

Following his JPL post-doctoral work, and as the company focused on developing standardized products, he said, "the gripper was really a prime candidate." He saw potential in automated manufacturing, where such a tool could offer advantages over conventional alternatives for lifting and moving objects on an assembly line, for example.

He licensed the underlying technology from Stanford and the California Institute of Technology, which manages JPL – the two teams had cooperated on the work. And Perception Robotics won Phase I and II Small Business Innovation Research contracts from JPL to fund further advances. In 2018, the company merged with Hungarian robotic sensor company OptoForce and Danish company On Robot, which specialized in finger-based robotic grippers. The Gecko Gripper debuted almost immediately thereafter, starting to take preorders that June, with the first units shipping at the end of the year.

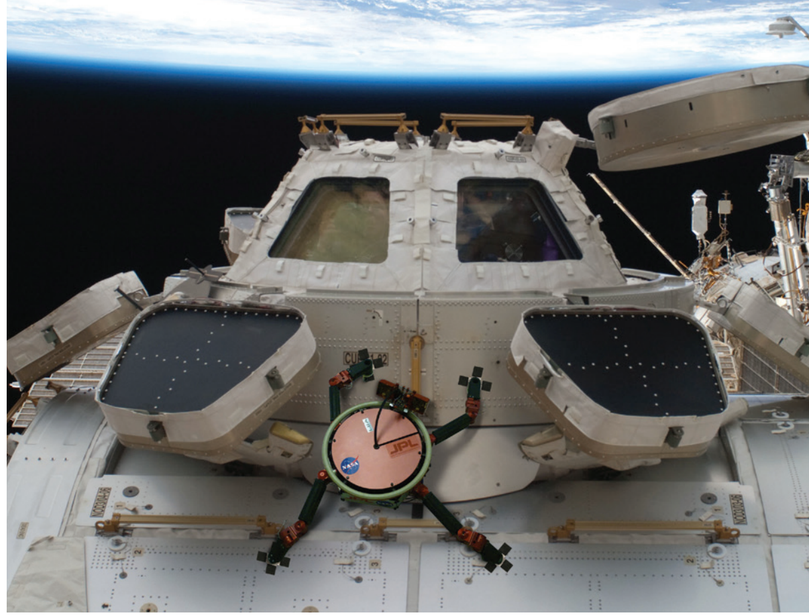
"I had never heard of anything like this prior to speaking with Nick," said Enrico Krog Iversen, CEO of the newly merged company, OnRobot, which is headquartered in Odense, Denmark, but produces the Gecko Gripper near Culver City, California. But he immediately saw its potential.

In particular, he saw a market in the manufacturing of printed circuit boards. These start out full of holes, so they can't be picked up with a vacuum gripper. Most circuit board manufacturers use finger grippers, but the Gecko Gripper could do the job quicker and with less programming.

14 Pounds of Grip

OnRobot is still improving the device and releasing new generations, but it's already come a long way. The gripper can achieve an adhesion force of 35 to 40 kilopascals on a polished surface, compared with a maximum of just four or five kilopascals at the time NASA started working on it. This makes it competitive with vacuum grippers. The company says it can easily lift polished metal weighing up to about 14 pounds.

The Gecko Gripper, based directly on technology developed by NASA and Stanford University, is now available for manufacturing facilities, where it can move circuit boards, solar panels, and many other smooth objects more easily than traditional grippers. *Credit: OnRobot A/S*



In this illustration, a Limbed Excursion Mechanical Utility Robot (LEMUR) climbs around the outside of the space station. JPL considered outfitting LEMUR with its gecko-imitating gripper technology. *Credit: NASA*

Wettels noted that this improvement is partly because the company has figured out how to apply even tinier tendrils to the ends of the microstructures, increasing their surface contact.

The gripper is equipped with an ultrasonic sensor to locate its target and a load sensor to determine its weight.

It's also able to activate and deactivate adhesion using the same technique as a gecko toe: the tiny fibers stick out at an angle, so they only adhere if they're pulled in the right direction. Pulled the other way, they'll release their hold.

"It's really cool to demonstrate it at a trade show, and people's eyes light up, and they're like, 'Whoa, that is magic,'" Wettels said, but he noted that even people working in robotics or manufacturing often don't intuitively grasp its usefulness.

If it replaces a Venturi pump – a common vacuum gripper that relies on compressed air – a Gecko Gripper pays for itself in seven to nine months, Wettels says. It's stronger than suction-cup grippers when loaded in shear, and the upcoming version runs on low enough power that it won't require an external cord, increasing its mobility.

He says the gripper easily grips anything flat and smooth, such as circuit boards, solar panels, glass, and metals, and it doesn't leave a mark on anything it grabs.

As the company continues to improve the technology and work it into different designs, and as more manufacturers become aware of it, Krog Iversen says he's confident it will catch on, given its advantages. "It allows us to handle applications that couldn't be handled by existing technology or had to be handled in a different way."

Meanwhile, NASA successfully tested its own version for long-term gripping ability in a year-long test on the International Space Station. A gecko-inspired technology is also being tested on the space station by integrating a gecko-style gripper with an Astrobee robot. Astrobee serves as a research platform that can be outfitted and programmed to carry such experiments in zero gravity.

Gareth Meirion-Griffith, who now manages the JPL climbers and grippers group, said human engineers can't take full credit for this remarkable technology: "If nature hadn't come up with this, I don't think anyone would have ever thought of it." ●

Planets Take Virtual Shape on Earth with NASA Knowledge and Imagery

Companies are creating virtual worlds with NASA's planetary data and augmenting our own, enabling immersive experiences of space

In a time of quarantines and online learning, guided strolls along the surface of Mars are especially appealing.

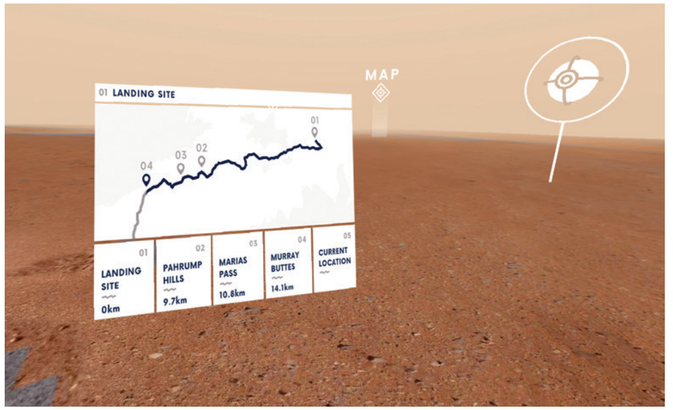
These tours are possible with Access Mars, a free virtual reality experience of the Red Planet, with interactive landmarks and narration by a NASA scientist, using the Planetary Data System (PDS).

PDS is a long-term archive of digital data products returned from NASA's planetary missions and actively managed by planetary scientists for the worldwide planetary science community. While all archived products are free and available online, PDS also provides a variety of tools useful in producing, obtaining, and using archived data.

The collaboration between NASA and Mountain View, California-based Google is one of numerous virtual and augmented reality projects made possible by the high-resolution imagery and data the space agency has collected with spacecraft and rovers on and around other worlds over the years.

Access Mars was created with photos taken by NASA's Curiosity rover, which has been studying the Red Planet since 2012. Users can navigate Curiosity's path, including the rover's landing site, its current location, and Martian landmarks like the Pahrump Hills, Marias Pass, and Murray Buttes, with wind hissing steadily in the background and explanations spoken by NASA scientist Kathryn Stack Morgan.

A Space Act Agreement enabled NASA and Google to collaborate on Access Mars, a virtual reality experience that allows just about anyone with an internet connection to explore the Red Planet.



Access Mars lets users navigate Curiosity's path, including the rover's landing site, its current location, and Martian landmarks like the Pahrump Hills, Marias Pass, and Murray Buttes. *Credit: NASA/JPL-Caltech*

Users only need a cellphone or computer and an internet connection, making the project broadly accessible, especially compared with traditional virtual reality experiences that require expensive headsets and large file downloads. This accessibility has come in handy for people feeling cooped up amid the pandemic of 2020.

"We saw a 15-times increase in visitors starting in mid-March," said Ryan Burke, creative producer at Google's Creative Lab. That uptick coincided with the first wave of stay-at-home orders in the United States to prevent the spread of the novel coronavirus.

The additional traffic is, at least in part, the result of teachers accommodating distance-learning situations and students and others looking for ways to learn and explore while maintaining social distance.

"Access Mars is very active Monday through Friday, while schools are in session, and then traffic dips a bit on the weekends," Burke said.

Getting NASA data into the hands of more people was always the point of the NASA-Google collaboration, which was formalized in a Space Act Agreement (SAA) with NASA Headquarters and is one of numerous SAA partnerships with the tech giant.

Working with private-sector organizations helps NASA get information about the agency's work to the public, and it can help keep that information up to date and accessible, according to Sasha Samochina, deputy manager of the Ops Lab at NASA's Jet Propulsion Laboratory in Southern California, which worked with Google on the Access Mars project.

Samochina and her team at the Ops Lab previously worked with Microsoft on a Mars app for the company's HoloLens, mixed-reality smart glasses that can function as a virtual reality headset. The HoloLens app, OnSight, allowed planetary geologists at NASA to study the surface of Mars by walking through the virtual terrain captured by Curiosity.

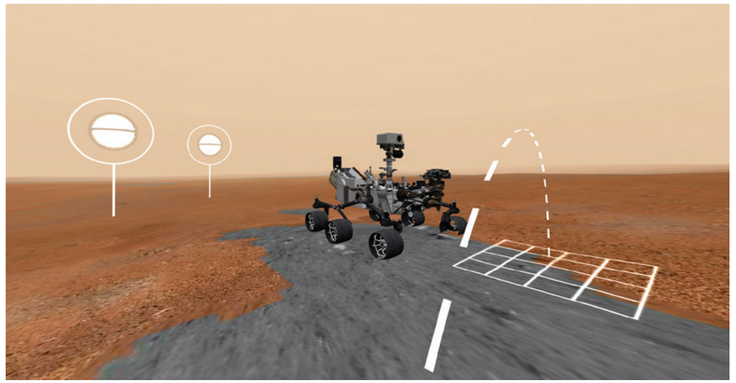
"Scientists could basically do site visits to places they were studying on Mars," Samochina said. "It was a first of its kind."

The OnSight app won NASA's software of the year award in 2018, and Mars scientists at NASA still use it to visualize and understand the terrain around the rover. However, besides a temporary exhibit at NASA's Kennedy Space Center Visitor's Center in Florida, it wasn't easily accessible to the public.

NASA shared the same Martian terrain data with Google to make an experience that's available to everyone.

The original files were too big for the web, so Google rebuilt the terrain data into smaller pieces. These smaller files load faster and use less data, giving a high-definition view of the surface of Mars to almost anyone with internet access.

"Our data is out there to be used," NASA's Samochina said. "The more accessible and the more understandable we can make it, and the more we can put it into easily digestible experiences, the better it is for us and for people who are trying to learn about what NASA is up to, what we're doing."



Google used terrain data from NASA's Curiosity rover to create Access Mars, rebuilding the imagery into smaller pieces that are easier to load over the internet. Clickable signposts along the way allow users to learn additional details about the Curiosity mission. *Credit: NASA/JPL-Caltech*

The World at Your Fingertips

NASA has also worked with several other companies to bring PDS data to life with virtual reality projects (as well as created its own browser-based Solar System Treks). The agency's robust repository of planetary imagery and data make it a natural partner for companies aiming to build other-worldly experiences. PDS currently holds 1.85 petabytes of data from over 70 missions and continues to grow, with millions of files downloaded by users every month.

Through another SAA, NASA partnered with Fusion Media Group Labs to create the Mars 2030 virtual experience. And sometimes NASA's public information is enough. Ireland-based Immersive VR Education created its Apollo 11 virtual reality experience almost entirely from images and drawings posted on NASA's historical web pages.

PDS datasets are also feeding the creations of AstroReality, a Cupertino, California-based company that sells intricate Moon and planet models with augmented reality features that are accessible through a cellphone app.

Hold a smartphone, with the app installed, over one of the company's detailed and heavy Moon globes, for example, and information about individual craters and other topographical features will pop up, in addition to general Moon knowledge.

"Rather than learning everything on a computer, we're trying to merge digital experiences with the best and most up-to-date data we can find with something you can hold in your hands," said J.R. Skok, AstroReality's chief science officer.

In creating its models, the company drew from NASA sources, like the Lunar Orbiter Laser Altimeter, or LOLA, which is onboard the Lunar Reconnaissance Orbiter that has been orbiting the Moon since 2009. LOLA has been gathering detailed topographical information that will inform the agency's decisions about landing sites for future lunar missions.

AstroReality uses publicly available NASA data to create models of the Moon and planets that pair with the company's apps, which provide additional information about specific lunar and planetary features.

Using augmented reality technology, AstroReality's LUNAR Pro Moon model can pair with the company's mobile app to reveal facts about individual lunar features and to simulate NASA missions. AstroReality drew from NASA data, including Lunar Orbiter Laser Altimeter data, to create the model and the app. *Credit: AstroReality*

"There's something the human mind gets when you can actually feel the craters on the Moon"

J.R. Skok, AstroReality

NASA data also helped shape AstroReality's Solar System Mini set. When paired with the mobile app, the models give users an immersive learning experience that includes a view of the solar system from the vantage point of each planet. *Credit: AstroReality*

The company has also consulted the Mars Orbiter Laser Altimeter, or MOLA, data for its Mars model topography, and NASA satellite imagery for its Earth model. LOLA, MOLA, and much of the agency's satellite Earth data are managed by NASA engineers at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

AstroReality's products also draw on NASA experience. Skok has worked as a NASA contractor and intern, and he received funding from the agency as a graduate student. He has used his knowledge of the agency's resources, including PDS, to help the company recreate celestial bodies with detail and accuracy.

In addition to planet models, the company sells augmented reality-enabled notebooks and mugs that also work with their cellphone apps.

While enthusiasts are the company's main customers, AstroReality also works with the Aldrin Family Foundation to bring space to children through schools and curricula.

"There's something the human mind gets when you can actually feel the craters on the Moon," Skok says. "There's an interplay between feeling it with your fingers, seeing it, and then getting the deeper detail through the technology. It creates a human experience, and that makes a difference." ●

Airports Go Digital

NASA's aviation expertise helps usher in digital communications at airports worldwide

Airport communications are getting safer and more efficient thanks to a new international technology standard developed with decades of NASA expertise, leveraged in a Space Act Agreement with the FAA and now used by private companies.

"NASA was one of the leading technology R&D agencies that validated AeroMACS. The agency deployed a system and tested it."

Declan Byrne, Worldwide Interoperability for Microwave Access Forum

Credit: Magnus Bäck

Some of the best entertainment at the airport is all the action outside the window. Loaded luggage carriers zip past on their way to planes. Fuel trucks come and go. Catering trucks restock galleys. During winter, de-icing crews and snow plows add to the bustle.

This organized chaos is overseen by the ground-control managers as part of an airport-wide effort to ensure the safety of all ground operations.

Coordinating all this activity is time-consuming and is a particularly challenging job at major airports with thousands of flights scheduled each week. Technology helps, but as air travel has increased, the challenge of keeping track of all the moving parts has only grown.

For decades, airports have relied mainly on voice communications over unsecured radio frequencies, with landline phone calls as the only secure backup option. However, a digital, wireless airport communications system developed in part by NASA is now poised to change the game. The Aeronautical Mobile Aircraft Communication System (AeroMACS) will allow Federal Aviation Administration (FAA) staff in control towers to send safety-critical information digitally and securely – and should lead to shorter wait times on the tarmac.

Breaking the Language Barrier

Just how far airport technology had fallen behind became too obvious to ignore when consumer cellular service became widely available.

"Children in the passenger cabin have megabit LTE cellular or satellite connections, but the bandwidth available to a pilot on the flight deck for communications is under kilobits per second," said Declan Byrne, president of the Worldwide Interoperability for Microwave Access (WiMAX) Forum. "That's alarming."

The forum, an independent industry group established to support and advocate for the adoption of AeroMACS technology, also certifies the new hardware created for airports. The FAA and other air traffic-control authorities around the world, along with NASA, participate in the forum.

AeroMACS will eventually phase out the use of voice communication as the primary method of information sharing for airport ground operations.

Air traffic control managers have communicated with airline pilots verbally for decades, but that's about to change. The Aeronautical Mobile Aircraft Communication System (AeroMACS) allows aviation authorities around the world to send safety-critical information digitally and securely to airplanes once they're on the ground. Telrad Networks is a technology provider that worked with NASA on the early testing of the system. *Credit: NASA*

The new, encrypted, high-speed digital data networks will streamline communications among ground crews and air traffic controllers. Messages sent to a pilot after the plane is on the ground can include diagrams and GPS-style maps, as well as text instructions for runway navigation, gate assignment details, and surface navigation directions.

When any airplane lands now, the pilot gets on a voice network and talks to the air traffic-control manager over a radio. "If you've got a German pilot trying to speak English to a Chinese air traffic controller, the possibility of miscommunication certainly exists," said Byrne, adding that a bad connection can compound the problem.

Aviation authorities from more than 150 countries chose and agreed to adopt the WiMAX standard. Formally adopted in 2007, WiMAX uses cellular network infrastructure that's customizable for the new frequency – the spectrum of 5091 to 5150 megahertz is reserved for safety-critical aviation communications only.

A New Hardware Toolkit

NASA engineers have been part of this process from the start. The agency's Glenn Research Center in Cleveland took the lead on AeroMACS testing. The center had worked on these issues previously and had extensive expertise, which made it a natural partner for the FAA. The two organizations signed a Space Act Agreement in 2007 to validate the new system and establish functional standards.

"NASA was one of the leading technology R&D agencies that validated AeroMACS," said Byrne. "The agency deployed a system and tested it. That work was essential for stakeholders in the international aviation community. It proved that this was a reliable standard they could support." To run the first aviation tests, NASA worked with the Broadband Wireless Access division of Alvarion Technologies Ltd. to modify existing WiMAX hardware. Acquired by Telrad Networks, the company was able to leverage its work with the agency to become one of the first to receive AeroMACS Wave 1 Certification.

In this family of hardware, any sensors called subscriber stations will collect, transmit, and receive data. Telrad builds the base station which performs the same function as in a cellular network, routing transmissions, with GPS providing timing for the network. The company also assists with identifying the best antenna type, and placement depends on the airport configuration and signal coverage needed around the surface.

A proxy client server executes banking-level security protocols and enables user authentication to verify the sender and receiver, blocking outside intrusions. The Access Service Network gateway enables connectivity throughout the network. This complete system customized by Telrad is all that's needed to set up an AeroMACS-based wireless network.

"Airports have a dedicated frequency allocated by government regulators that is free of charge for them to use," said Yishai Amsterdamer, general manager of Telrad's Broadband Wireless Access division. "Each one can develop it for themselves."

The Israeli company, which has an office in Delmar, New York, is now working with airports around the world to customize system configurations.

Telrad has also created Star Suite, a software network management program that can support any application an airport might require.

A 20-Year Job

AeroMACS is cheaper to operate and maintain than existing voice-based infrastructure, but it will take time to transition all airports to the new technology. Each aviation authority may choose to implement it in smaller stages. So far, some U.S. airports are using the system to collect information from surveillance sensors, which will help improve aircraft tracking on runways and taxiways, explained Rafael Apaza, principal investigator and senior communications research engineer at Glenn.

AeroMACS technology will one day allow all of the many ground operations at airports to communicate digitally and securely. *Credit: ugurhan via Getty Images*

And for the first time, in 2016, NASA successfully transmitted aviation data, including route options and weather information, to a taxiing airplane over a wireless communication system. The sophisticated electronics used in airplanes are highly sensitive, so inexact wireless communication could disrupt those systems. Successfully eliminating the risk of signal interference while maintaining throughput capacity was what made this accomplishment so significant. Only then was the system proven safe for airplanes.

The Telrad BreezeCOMPACT 1000 4G broadband base station, a modem and radio all in one, was named Product of the Year by the Wireless Internet Service Providers Association. *Credit: Telrad*

NASA engineers also proved that mobile assets such as emergency vehicles and laptop computers could be included in the wireless network. This will make it possible to track specific assets when they're needed.

To date, more than 50 airports in about 15 different countries are using AeroMACS to replace voice with data transmission. It's estimated that it will take 20 years to transition over 40,000 airports worldwide.

When it's fully implemented, it will be able to swiftly and securely route any ground communications.

A three-month pilot program at the Beijing Airport deployed the system for mobile assets and found that using AeroMACS instead of voice commands shaved 20 minutes off the time planes were spending on the ground – a huge cost and time savings.

As aviation authorities such as the FAA publish AeroMACS guidelines, Telrad and other hardware providers will be able to develop new tools to support the use of wireless communication at airports. Innovation will take off, according to Amsterdamer.

"This is going to be millions of dollars in innovation. When this is adopted by the airline companies, then the business can grow."

Food Safety Program for Space Has Taken Over on Earth

System created for Apollo astronaut food has become the global standard for hazard prevention

As many Americans prepare for a socially distanced Thanksgiving meal, some may be aware that NASA helped develop the tiny, highly efficient video cameras in the devices that will allow virtual family dinners, and a few may know it was the space agency that first modernized conference calling. But NASA has made an even more important contribution to the holiday: no one is likely to worry about the safety of the food on their table.

Today, outbreaks of food poisoning from packaged supermarket food are exceedingly rare, thanks in part to the food industry's near-universal adoption of an approach that's little-known outside the business, called the Hazard Analysis and Critical Control Point (HACCP) system. Even less-known is the fact that HACCP was created for astronaut food in the early days of the Apollo program.

This means all the companies putting food on your Thanksgiving table, from the people who bring you your turkey to the folks behind your cranberry sauce and stuffing, use HACCP – and cite it as a major reason for the reduction in foodborne illness.

Credit: fiadendron via Getty Images

Facing strict reliability requirements, NASA and Pillsbury personnel invented a system to prevent hazards from entering foods processed for the Apollo astronauts. Their approach now assures safe processed foods all over the world.

"While the average consumer may not know what HACCP is, we know it's enabling us to consistently put out safe, quality product," said Ocean Spray vice president of research and development Katy Latimer.

"It's one of these things where we maybe don't appreciate the benefits, we just take them for granted now, because HACCP is so ingrained in how we produce food," said Alice Johnson, vice president of food safety and quality at Butterball Turkey LLC.

Mark Fryling, vice president of global food safety and quality at General Mills, added that his company has HACCP in mind from the moment it starts developing a product, in large part because "one of the key aspects that distinguishes HACCP is that it's very prevention-oriented."

That focus on prevention comes from the system's original motivation: avoiding food poisoning on the way to the Moon.

And in a way, General Mills has longer experience with HACCP (pronounced "hás-sip") than any other company. It now owns Pillsbury, which partnered with NASA in the early 1960s to provide safe food for the astronauts on the Gemini and Apollo missions.

The Hazard Analysis and Critical Control Point (HACCP) food safety system, which stemmed from requirements for the Apollo program, now underlies food safety programs and regulations for virtually all meats, poultry, fish, and processed foods, including many Thanksgiving dinner staples. *Credit: AlexRaths via Getty Images*

Analyze Hazards, Establish Control

Leading the effort at the Manned Spacecraft Center, now NASA's Johnson Space Center in Houston, was Paul Lachance, former coordinator for the U.S. Air Force's Quartermaster Food and Container Institute. That institute had just moved and become the U.S. Army Natick Laboratories, which NASA brought on board as a partner in developing food for the space program.

Lachance's background in nutrition was complemented by that of Howard Bauman, the microbiologist who was heading Pillsbury's part of the work. "So he was an ideal person, in some ways, to develop a laboratory where microbiology had to be paid attention to," Lachance said in an interview for Johnson's Oral History Project. "He had to do that initially for Gemini, and so he really had a feeling for how to do it for Apollo."

In the early Gemini days, Lachance recalled, his team focused on thoroughly testing end products, destroying one batch after another when irregularities were found. The team had started examining its food production processes for points where contamination could be introduced, but Apollo expanded this approach and made it mandatory.

Beginning in 1963, the Apollo Program Office issued a series of guidelines for all the program's contractors, aimed at ensuring reliability in all critical mission systems. Based in part on a system developed by the military, known as Failure Mode and Effects Analysis, these heavily emphasized identifying and controlling any potential points of failure. While the NASA guidelines were written primarily with space system hardware in mind, food was also deemed mission-critical. So Lachance and Bauman found themselves applying spacecraft-level reliability assurance to astronaut food.

They came up with three guiding principles: Conduct a hazard analysis, looking for points in the process where any type of hazard could be introduced. Identify those points and determine how hazards can be prevented, controlled, or eliminated at each one. And monitor these critical control points with frequent measurements. NASA also required the team to keep meticulous records of all this work, which became another critical aspect of HACCP.

No one in the Apollo Program Office could have imagined they had set in motion a system that would improve food safety around the world – and it took decades for that to happen. But Bauman liked what he saw.

"Quality control within the food industry had been based primarily on testing the end product," he wrote in a 1987 article in the trade publication Cereal Foods World. "We found we could establish a better system, but it would require a hazard analysis on each product and each line."

Bauman went on to become one of the most outspoken advocates for HACCP's widespread adoption. But he first successfully pushed Pillsbury to take on this new approach.

Food for the Apollo astronauts was not always especially appealing, but thanks to the hazard prevention system NASA and Pillsbury came up with, it was always safe. *Credit: NASA*

A Slow Start, and then Rapid Acceleration

The company presented HACCP to the world at the first National Conference on Food Protection in 1971. It was not immediately embraced, but after two deaths from botulism caused by canned soup that summer, the National Canners Association petitioned the Food and Drug Administration (FDA) for regulations to prevent food poisoning. The FDA in turn asked Pillsbury to train its supervisors and food inspectors on the system it had developed for NASA.

In 1973, low-acid canned food manufacturers became the first to be subject to HACCP regulations, and they were the only ones for a long time. Then in 1993, an outbreak of food poisoning due to a Shinga toxin-producing strain of *E. coli* bacteria caused the meat and poultry industries to lobby for regulation to restore consumer confidence. Within a decade, the U.S. Department of Agriculture (USDA) had HACCP regulations in place for meat and poultry, and the FDA required the system for all seafood and juice producers. By then four additional principles had been adde to clarify NASA's original three, including establishing critical limits at control points and keeping records not just on food production but on a plant's HACCP plan itself.

Then came the 2011 FDA Food Safety Modernization Act. Although it doesn't mentic HACCP by name, opting instead for the term Hazard Analysis and Risk-Based Preventive Controls, the law effectively phased in HACCF like requirements across all the remaining U.S food producers that have to register with the FDA. The law also requires importers to verify that foreign manufacturers comply with these requirements. The last businesses were phased into the requirements in 2018.

"It basically mandates HACCP on steroids for all other FDA-regulated food products," said Jenny Scott, senior advisor in the FDA's Office of Food Safety, although she noted that many producers – including all the major ones in the United States – had long before put HACCP-like systems in place voluntarily and required their suppliers to do likewise.

"Brainstorming What Could Go Wrong"

Food processing plants today don't simply copy the steps NASA took to ensure astronaut safety. That's not how HACCP works. The system is intended to target the specific hazards in a given production line, so every HACCP plan is different, not just from one company to another but from product to product. At a Butterball plant, Johnson said, control points as prerequisites for a HACCP plan likely include, for example, a checkpoint to look for any "farm residue" like pesticide, refrigeration that has to be below a certain temperature, and antimicrobial sprays or dip tanks.

Latimer noted that Ocean Spray adopted HACCP for all of its products when the FDA started requiring it for juice in 2001.

Critical control points to monitor for cranberry sauce production can include a washing station for the berries, filtration and metal detection that ensure against foreign materials, heat treatment for pasteurization, and checks of acidity levels, among others. *Credit: TatianaMironenko via Getty Images*

Critical control points for cranberry sauce include the washing area where berries are first received, filtration and metal detection points where foreign materials are removed, a heat treatment pasteurization area, and acidity level checks, among others, she said.

General Mills has three plants making Honey Nut Cheerios in North America, and each has its own separate HACCP plan to account for differences between the plants, said Fryling. "That's a requirement of HACCP. You have to analyze the risks of that line and that product."

In this way, Johnson said, the adoption of HACCP regulations changed companies' relationship with regulators. "The whole industry no longer relies on the government to tell us what we've got to do," she said. "Instead of going to the government and saying, 'We've got a problem, what do you think we should do?' it's up to us to decide what to do and justify why we're doing it."

But it's not a simple task. "It takes a team of quality assurance folks, engineers, and scientists to identify critical control points for safety and quality," said Latimer, calling it a process of "brainstorming what could go wrong."

A HACCP plan for turkey processing means monitoring crucial points such as those where any residual farm chemicals are removed, proper refrigeration must be maintained, and antimicrobial sprays or dip tanks are used. High-pressure processing has recently become popular for poultry and various other foods as a way to eliminate potential pathogens and extend shelf life. *Credit: Iisegagne via Getty Images*

Pie crusts are among several Thanksgiving staples made by Pillsbury. Now owned by General Mills, Pillsbury worked with NASA to develop the HACCP system to ensure safe astronaut food. The company subsequently adopted the system and became a major advocate for its wider adoption across the U.S. food industry and around the world. *Credit: GMVozd via Getty Images*

While it takes time and money, Fryling said the price is dwarfed by the cost of a product recall and the resulting damage to a brand name. "I don't get challenged on the cost of hazard prevention by managers of this organization," he said.

To help plants develop their safety plans, a number of nonprofit and trade organizations offer HACCP training, and the FDA and USDA make various resources available to smaller businesses, from help desks to in-person informational visits. "We consider outreach to small establishments essential," said Scott Seebohm, deputy director of the policy development staff for the USDA's Food Safety and Inspection Service. "Small and very small plants promote rural businesses and the rural economy. That's something we all have an interest in promoting."

HACCP also makes inspections much more effective. In the pre-HACCP days, for example, plants weren't required to keep safety-related records, said Scott at the FDA, noting that inspectors only saw a snapshot of what conditions were and what was happening the day of their visit. Now plants have to present reams of data. "We still poke and sniff, but records give a better picture of whether they're consistently in control of their processes," she said.

Going Global

Scott said it can be difficult to put a number on the results of HACCP implementation, because while industry has gotten better at preventing outbreaks, the Centers for Disease Control and Prevention have gotten better at detecting them. Between the early to mid-1990s and the early 2000s, for example, while there was generally an increase in the annual number of known outbreaks caused by *Salmonella* – the most common cause of foodborne illness – the number of confirmed cases due to those outbreaks dropped.

Results continue to improve. As top-priority hazards, such as *E. coli* in the 1990s meat industry, are brought under control, both producers and regulators can tighten standards and refocus on smaller problems, Seebhom said. He added that the shift to HACCP also moved some responsibilities for quality control and aesthetics from regulators to the companies, further freeing up inspectors to verify company control of potential dangers.

Because HACCP requirements give industry a general approach to achieve food safety without telling companies the specific steps they have to take, he said, it has allowed flexibility for them to come up with new methods and techniques, which have improved continually.

A technique that's caught on in recent years is the use of high-pressure systems to kill off bacteria, said Johnson at Butterball. The equipment was costly up front but further reduces the kind of waste that's necessary when a hazard is found in an end product.

Scott at the FDA said there's still room for improvement. Her agency is in the early stages of enacting requirements for preventive controls around food allergens – which account for about a third of FDA recalls. And the Food Safety Preventive Controls Alliance, which the FDA created in 2011 to bring together federal and state regulators, academia, and industry, continues to improve training for both inspectors and producers. The FDA also continues to publish more detailed guidance for companies.

Meanwhile, this spinoff from the Apollo food safety program has gone global: much of Europe took up HACCP many years ago, and many other suppliers around the world use HACCP-like systems to be allowed to export to the U.S. and Europe.

Latimer at Ocean Spray said the packaged-food industry was originally born out of deaths from botulism caused by people using unsafe practices. "It's really cool to see how the space program moved that along," she said, noting that a small NASA program helped the industry make good on its most basic promise – that of safe, worry-free meals, on Thanksgiving and all year round. ●

The Seven Principles of HACCP

Principle 1: Conduct a Hazard Analysis

List all steps in the process and identify those where hazards might be introduced. Identify possible control measures.

Principle 2: Identify the Critical Control Points (CCPs)

Identify points, steps, or procedures where hazards can be prevented, eliminated, or reduced to acceptable levels. A CCP may control more than one hazard, or more than one CCP may control a single hazard.

Principle 3: Establish Critical Limits

These are the maximum and/or minimum parameters under which each CCP can produce safe food. Limits are usually measured in time, temperature, pH, or other measures based on science or regulations.

Principle 4: Monitor CCPs

Develop procedures to ensure each CCP remains within its critical limits. Decide how, when, and how frequently each measurement is taken.

Principle 5: Establish Corrective Action

Describe the steps that will prevent hazards from entering the product in the event of a deviation from critical limits. Describe the steps to correct the process and ensure the problem won't recur.

Principle 6: Verification

Determine that the HACCP plan is valid and that the system is operating accordingly. This may include reviewing records, auditing CCPs, calibrating instruments, testing products, and more.

Principle 7: Recordkeeping

Record information proving food was produced safely. Include procedures and policies; records of training, monitoring, and sampling; invoices and receipts; and information about the implementation of all seven HACCP principles, including recordkeeping.

Spinoff Technology Across the Nation

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6	Answering the Call of Distress	Software to improve search and rescue	Orbit Logic, Greenbelt, MD
7	Catch the Waves	Isolators for spectrum sensors	Micro Harmonics, Fincastle, VA
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13	Fix It like an Astronaut with Augmented Reality	Augmented reality procedures program	Tietronix Software, Houston, TX
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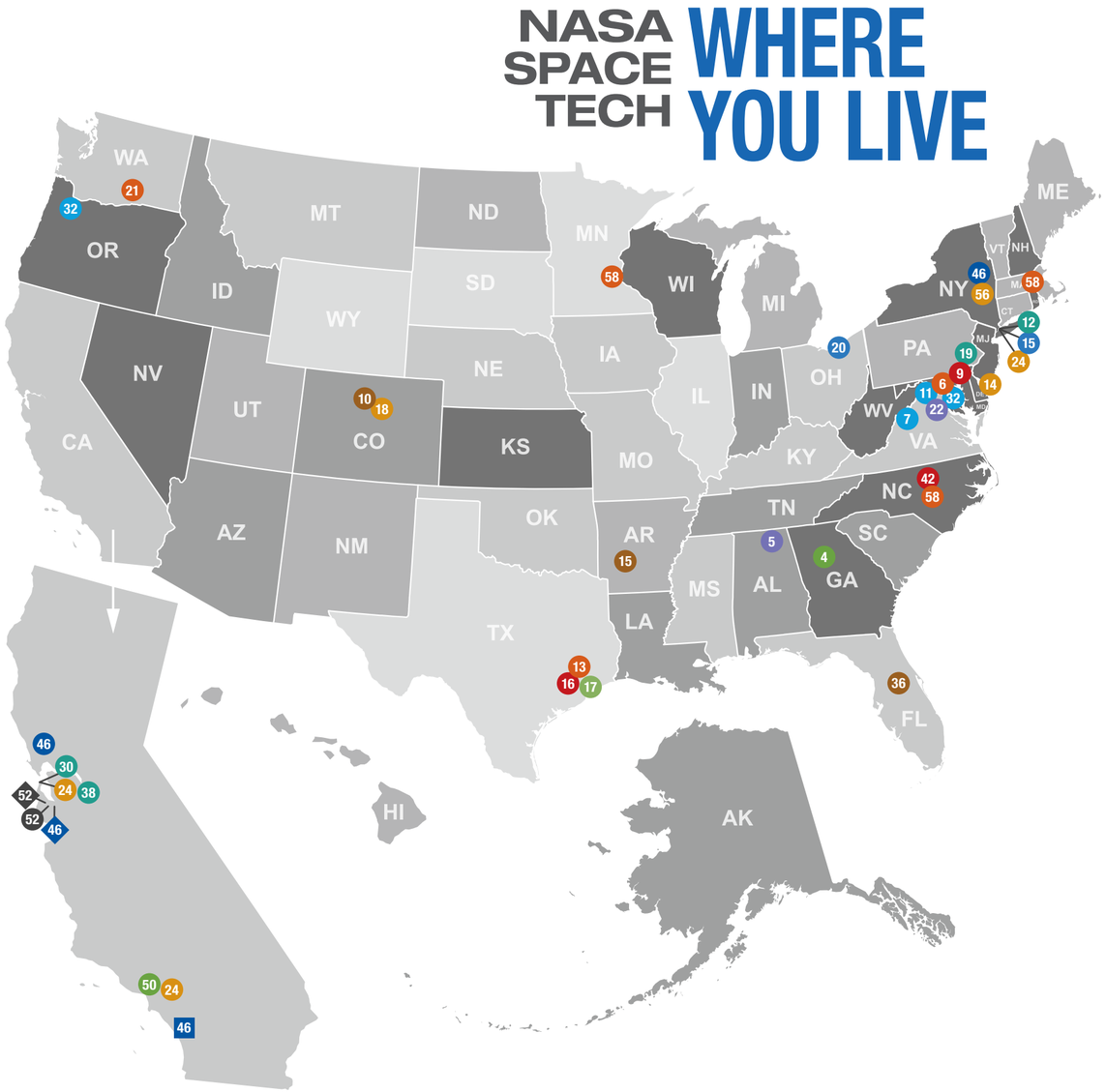


The SpaceX Crew Dragon, the Japanese H-II Transfer Vehicle-9 resupply ship, and Europe's Columbus laboratory module figure prominently in this photograph taken during a spacewalk with astronauts Bob Behnken and Chris Cassidy. All three are attached to the U.S. Harmony module with the International Docking Adapter on top.

Technology Transfer Program

NASA's portfolio includes over 1,000 patents and hundreds more software codes, with new additions being filed every year. The Technology Transfer Program works tirelessly behind the scenes to market this revolutionary technology to maximize its benefit across the country and around the world. This year that took on special meaning as the world faced a historic pandemic – and the program pivoted immediately to finding and adapting NASA technology to help.

Inside NASA's Pandemic Response Campaigns

Marathon efforts, new approaches, old expertise are poised to pay off

"When the problem is translated to physics, we know what to do."

Leon Alkalai, Jet Propulsion Laboratory

In mid-March, as much of the country shut down in response to the rapidly spreading novel coronavirus, a team of engineers at NASA's Jet Propulsion Laboratory in Southern California got to work.

Doctors nearby needed ventilators, so the team set out to design an inexpensive version that wouldn't use any of the same parts as traditional ventilators, so as not to compete for supplies.

Unsure where to begin and knowing that whatever they came up with would need rapid approval, they reached out to the Food and Drug Administration (FDA). Leon Alkalai, head of strategic partnerships for JPL, connected with the regulator's assistant director in charge of respiratory devices. "I said, 'We have no idea what we're doing, but we have a great team and we're enthusiastic and we need help,'" Alkalai recalled, "and he said, 'We're in.'"

The FDA official noted that ventilator design is essentially "a physics and fluidic problem," Alkalai said. That was when he knew the team would succeed. "When the problem is translated to physics, we know what to do."

About 30 entities have licensed the low-cost Ventilator Intervention Technology Accessible Locally, or VITAL, that Jet Propulsion Laboratory (JPL) engineers designed and patented. Licenses are free of charge. *Credit: NASA*

Across NASA, other centers also found ways to refocus their skills and technologies to address the pandemic. As rates of infection and hospitalization remain high in many states, several of the solutions NASA field centers came up with in the spring now teeter on the verge of widespread application.

At NASA's Johnson Space Center in Houston, home of the Human Health and Performance Center, the Technology Transfer Office combed through more than 2,000 technologies and software programs created in the last decade, looking for anything that might be useful in confronting the health crisis. The center submitted a portfolio of 34 open source technologies to the United Nations and is also helping a handful of groups update and manufacture a simple, human-powered ventilator originally designed for the space program.

Meanwhile, NASA's Armstrong Flight Research Center in Edwards, California, joined a local public-private task force with a hospital and college, a neighboring city, and two spaceflight companies and ended up patenting an improvement to an oxygen helmet for COVID-19 patients.

And when NASA's Glenn Research Center in Cleveland heard that a familiar company was working to update a device for sterilizing medical equipment and spaces, the center jumped in to help.

In all these cases, NASA and its partners found that, with a little guidance, aerospace engineers also make pretty good medical engineers.

If It Helps Save One Life

For JPL, quick turnaround of a viable emergency ventilator meant reaching out to many partners, said Alkalai, who initiated and managed all these relationships. These included two local hospitals, several federal agencies, the University of California Los Angeles, and medical device giant Medtronic.

After just 37 days of working around the clock, they had a prototype, called Ventilator Intervention Technology Accessible Locally, or VITAL for short. "There were issues of exhaustion, but we were on a mission," Alkalai said.

Almost as quickly, the FDA granted the device a ventilator emergency use authorization. The next trick was to get it out into the world. This required a new approach to licensing.

"Normally, we're happy if just one company comes to us saying they're interested in a license," said Daniel Broderick, manager of JPL's Technology Transfer Office. In this case, the response was much bigger. Over 300 companies registered on the JPL website to learn more about the ventilator, and more than 100 applied for a license. Now the challenge was to determine who was capable of producing the machine. "We've never seen this much licensing demand for a technology," Broderick said.

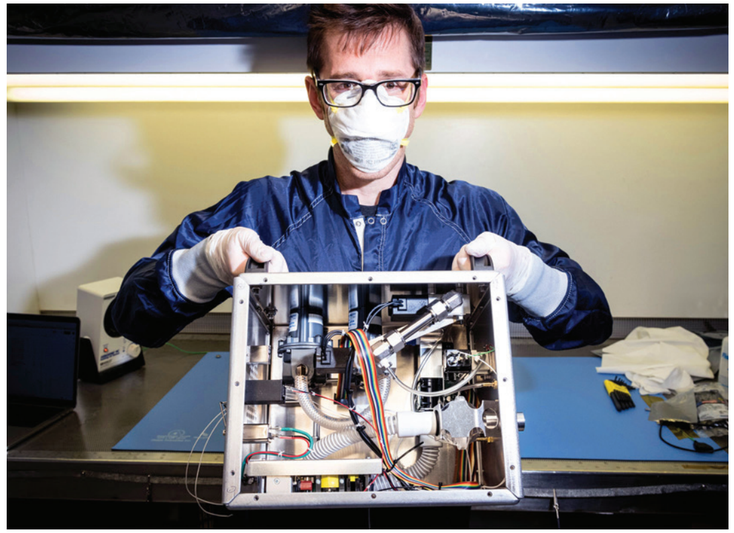
One of those applicants was Pro-Dex Inc., a design and manufacturing company in Irvine, California. Working with NASA on the ventilator was an opportunity to learn new things, grow the company, and "be part of the solution," said Pro-Dex CEO Rick Van Kirk.

In late June, the company was working on sourcing parts, determining distribution channels, and laying out the assembly line. And NASA is still supporting the effort, having put together documentation, 3D renderings, and videos to assist licensees, including a video about the assembly process. "They did a great job of teeing it up for everybody," said Van Kirk.

Pro-Dex was one of 29 companies granted licenses, including seven other U.S. businesses.

"If half of them end up delivering the devices, that would be amazing," said Alkalai. "We would be just thrilled if at least one unit makes it into a hospital and helps save a life."

Other teams at JPL have designed protective respirator masks and a necklace that vibrates when wearers start to touch their faces. The masks and necklace can be 3D printed, and the design files and instructions are available for open source licensing on GitHub.



Patrick Degrosse, engineer at JPL, shows the guts of the ventilator that a team of NASA engineers designed in just over five weeks. The machine uses none of the parts used in traditional ventilators, so as not to compete for supply lines. *Credit: NASA*

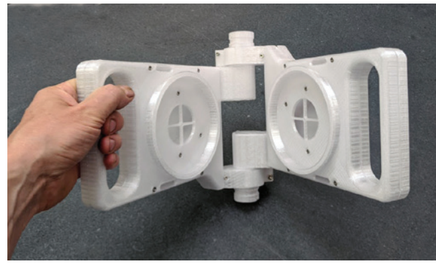
Human-Powered Solutions

Engineers at Johnson are offering a simpler ventilator solution, primarily for use in developing countries. As the pandemic unfolded, engineers who had developed a ventilator for use on the Orion spacecraft started updating it. The device is similar to human-powered ventilator bags used in ambulances, but those are squeezed by hand, which becomes tiring quickly. Johnson's ventilator is powered by larger muscle groups in the arms or even legs. It can be used to keep a patient alive for hours, perhaps while waiting for a bed to open up, said Kris Romig, technology transfer officer at Johnson.

"The technical team came to us and said, 'We think this could help, and we don't know how to get it out into the world,'" he said. The center is now offering the ventilator as an open source technology.

It didn't take long for Matthew Fiedler and the other founders of 3D printing company re:3D, all former Johnson employees, to hear about the ventilator, which the company is helping to refine.

The Johnson team had computer-aided design files for the ventilator parts but had never manufactured them. "They sent us the file, and we printed it," Fiedler said. "We're helping them bring the product to life and figure out how to make it better."



A team at Johnson Space Center designed a 3D-printable ventilator that can be powered with both hands for use in the Orion capsule. The center has repurposed it for use on COVID-19 patients and is working with companies around the world to get it out to hospitals. Only a few parts, such as the accordion-like bellows, can't be 3D printed. *Credit: re:3D*

Once the design is finalized, re:3D, whose manufacturing facility is close by Johnson in Houston, could start producing ventilators, working with federal and international organizations to get them into the hands of those who need them, he said.

Anheuser-Busch InBev (ABI), whose global technical headquarters is in St. Louis, Missouri, is also working to get Johnson's manual ventilator out into developing countries. "We deliver beer to places you wouldn't believe all over the world," said Lucas Steinle, global director of industrial digital transformation at ABI, noting the company could use that infrastructure to help deliver the ventilators almost anywhere.

The engineering group of ABI's subsidiary in South America, known as Ambev, is working with Johnson engineers to finalize a prototype, which it plans to bring to the United Nations to see how the company can partner with other groups to get it into manufacturing and distribution. Steinle added that ABI has the facilities to manufacture it through 3D printing if need be.

Meanwhile, Leviathan Space Industries is building partnerships to introduce the human-powered ventilator in Ecuador. The company has been working to build a private spaceport in the Ecuadorian city of Guayaquil, which was ravaged by one of the world's worst outbreaks of the virus.

"Due to its ease of use and how cheap it is, this can definitely help provide emergency relief when hospitals have overflow capacity," said Robert Aillon, founder of Leviathan.

The Pompano Beach, Florida-based company has partnered with the University of Kentucky for help with testing and FDA approval and is working with Ecuadorian company Pica Plasticos Industriales on manufacturing. And Leviathan is working with the Ecuadorian school Universidad Espiritu Santo to help with that country's regulatory approval process, Aillon said.

Back at Johnson, the center's simultaneous effort to dig up any technology that might help – whether or not it's patented – has led the Technology Transfer Office to consider making it possible for the public to search broad categories of unpatented technology. "These can be useful without a license, just open source," Romig said.

A Second-Generation Sterilizer

While others work on ways to mitigate the effects of the virus, the company Emergency Products and Research (EP+R) is working with Glenn engineers to destroy it.

The Kent, Ohio-based company's AMBUstat fogger system creates an aerosol of water, peracetic acid, and hydrogen peroxide to eliminate all pathogens in the air or on surfaces. It was originally developed after consultation with a Glenn research engineer in 2015 and was intended for use in ambulances.

"We were working on a new design that would let us deal with the limitations of the original," said Jason Thompson, who handles business development for EP+R and drove the original device's creation. The company wanted it to better address airborne contaminants, treat different-sized spaces more efficiently, and be more cost-effective.

With help from a Glenn Research Center engineer, the company Emergency Products and Research (EP+R) improved its AMBUstat sterilizing fogger. The new AMBUstat G2 is better at eliminating airborne contaminants and adjusting to different-sized spaces. *Credit: Emergency Products and Research*

Jason Thompson of EP+R tests a new system that lets the AMBUstat G2 fogging device quickly sterilize small spaces, like the inside of a police car. *Credit: Emergency Products and Research*

When Glenn heard about the new work, the center wanted to help again, so it put an aerosol science and instrumentation specialist on the case, and JPL was tapped for additional consulting. The resulting device, known as the AMBUstat G2, creates smaller aerosol droplets to better attack airborne viruses. Improved flow control and the ability to control the process from outside of the targeted space allow it to treat spaces faster and more effectively. In a pilot project with the Ohio State Highway Patrol, the company found it could disinfect 10 to 12 police cars in the time the original fogger treated just one.

Following about a month and a half of cooperation, Glenn is testing the new device, after which it will go to a proving ground for testing against the novel coronavirus.

With the sterilant already approved by the Environmental Protection Agency, Thompson said, the company is ready to move into production of the AMBUstat G2 as soon as testing is complete.

Meanwhile, the Glenn researcher who helped refine the original AMBUstat teamed up with researchers from University Hospitals Health System in Cleveland to develop another device that uses atomic oxygen to decontaminate N95 facemasks for reuse. Initial results indicate effectiveness; however, more testing is needed to confirm the effect of multiple decontamination cycles on the integrity of the masks.

"Completely Outside of Our Comfort Zone"

Over at Armstrong, the Technology Transfer Office was hard at work pursuing FDA approval and a company to build an improved oxygen-supplying device the center's engineers came up with.

The positive-pressure oxygen helmet resulted from a task force that included Armstrong, spaceflight company Virgin Galactic and its sister The Spaceship Company, the city of Lancaster, Antelope Valley Hospital, and Antelope Valley College, bringing together resources, medical professionals, and engineers.

Oxygen helmet manufacturers have been unable to meet the surge in demand in response to COVID-19, which often deprives patients of oxygen. A team led by Armstrong engineer Mike Buttigieg was charged with developing a low-cost, easily made assisted breathing helmet that could withstand pressures that off-the-shelf units weren't designed for, without impacting the supply chain. Through conversations with the team's lead doctor, Buttigieg had the idea to install a magnetic port, allowing access to the wearer's face.

"Having a helmet on without face access makes it hard to check vitals or take a drink of water," said Samantha Hull, licensing manager and outreach coordinator at Armstrong.

The task force produced hundreds of the modified helmets for use at local hospitals, but Armstrong wanted to get them produced at greater scale. Final FDA approval also required a commercial manufacturer, meaning NASA had to find a company to license the technology without regulatory approval, said Benjamin Tomlinson, technology transfer officer at Armstrong.

In early July, the brand-new company Medify Products LLC signed a nonexclusive license to use the magnetic access port in oxygen helmets.

Tom Ryder, president and CEO of Genesis Plastics Welding, started Medify Products after he saw video of oxygen helmets being used in Italian hospitals early in the crisis. Genesis, his original company, had been producing similar helmets for more than 25 years.

"This is a product that utilizes all of our expertise," he said. "We want to put that talent to use in fighting the virus."

Ryder said Medify, located in Fortville, Indiana, will likely incorporate Armstrong's magnetic port into more than one helmet design. A major advantage of working with NASA, he said, is that Armstrong is working with its contacts to get prototypes into formal testing and working with the FDA to secure emergency use authorization for the helmets.

Much of this is new territory for Armstrong, which specializes in aeronautical research. "Medical applications are completely outside of our comfort zone," said Tomlinson, noting that his team is figuring out how to navigate the approval process.

"This is something you can produce without a lot of expense, and it can save lives," said Tomlinson. "Its elegance and simplicity is the beauty of it."

Ryder said he wouldn't previously have associated NASA with projects like this. "How they're working with businesses like mine, a small business, gives me hope for the country." ●

Armstrong Flight Research Center engineer Mike Buttigieg, left, led a team that came up with a low-cost oxygen helmet for COVID-19 patients. The design includes a magnetically sealed port, which the center has licensed out. Here, Dr. Daniel Khodabakhsh of Antelope Valley Hospital tries one on. The hospital was part of a task force that helped with the effort. *Credit: NASA*

"This is a product that utilizes all of our expertise. We want to put that talent to use in fighting the virus."

Tom Ryder, Medify Products

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BRINGING NASA TECHNOLOGY DOWN TO EARTH

Spinoffs of Tomorrow

Each year we document dozens of spinoff success stories, but the work of the Technology Transfer Program is ongoing. Our technology portfolio contains many exciting innovations ready for an enterprising company or entrepreneur to license and develop into a commercial product.

This section features 20 examples that we think show great promise.

To learn more about – and get started licensing – these or any of the others in our extensive portfolio, please visit **technology.nasa.gov**.

Ames

Preventing Traffic Jams in the Sky

National Airspace System Constraint Evaluation and Notification Tool (NASCENT)

NASA's National Airspace System Constraint Evaluation and Notification Tool (NASCENT) automatically analyzes routes of aircraft that need to fly in or near constraint regions and attempts to find more time- and fuel-efficient reroutes around current and predicted constraints. NASCENT provides an evaluation of avoidance routes that save more than a user-specified number of minutes of flying time for all 20 Air Route Traffic Control Centers in the national airspace system simultaneously.

The system continuously analyzes all flights and provides reroute advisories that are updated in real time. It includes a graphical user interface that allows users to visualize, evaluate, modify if necessary, and implement proposed reroutes.

Benefits

- Fuel savings and reduced delays
- Environmental emissions reduction
- Real-time congestion management, updating every minute
- Nationwide simulation and analysis capability

Applications

- Aerospace industry
- Air traffic management
- Airline dispatchers

Benefits

- Supports geographically geofenced area on a continuous basis
- Lets drones reliably provide communication, navigation, and surveillance below 10,000 feet
- Procedures and airspace design to keep drones separated from each other and general aviation
- Plans routes to avoid conflict, collision, terrain, obstacles, severe weather, and wind based on needs of UAS operation and capability

Applications

- Aerial imaging and mapping
- Law enforcement
- Communications and newsgathering
- Delivery of goods and services, from freight to medicine

Directing Drone Traffic

Unmanned Aerial Systems Traffic Management

NASA has developed a traffic management system for unmanned aerial systems (UAS), or drones, to maintain safe and efficient operations. This novel technology enables civilian applications of UAS operations to grow at lower altitudes by developing a UAS Traffic Management system. This system could be used for delivery of goods and services, agricultural imaging and surveillance, and utility management.

Armstrong

Benefits

- Adjusts control in response to real-time environmental changes
- Increases performance and fuel savings for flight applications; optimizes performance for other applications
- Allows for design of all dimensions of the process simultaneously
- Allows implementation for aircraft at relatively low cost

Applications

- Aerospace, aeronautics, and automotive systems
- Manufacturing
- Chemical engineering
- Tissue and biochemical engineering

Finding Peak Performance

Approach to detect environmental changes in real time to adjust and improve performance

Innovators at Armstrong Flight Research Center have developed and are patenting a peak performance-seeking algorithm that can optimize the performance of complex systems in real time. Originally designed for aircraft flying in formation, the algorithm can automatically find optimal formation configurations to reduce aircraft drag, increasing fuel efficiency.

The method is capable of using real-time measurements and quickly adapting to changing environmental conditions. In addition to aerospace applications, including commercial flight, this technology could also be used in situations where optimization is critical, such as in feedback control systems for manufacturing, business processes, energy management, and the automotive industry.

Low Power, High Fidelity

Software for aeronautics collision avoidance and a range of research areas

Data-adaptive algorithms are critically enabling technology for automatic collision avoidance systems. Available for licensing, these Armstrong-developed algorithms provide an extensive and highly efficient encoding process for global-scale digital terrain maps, along with a real-time decoding process to locally render map data. The algorithms are designed to be easily integrated into an aircraft's existing onboard computing environment or into an electronic flight bag or mobile device application.

In addition to its use within next-generation collision avoidance systems, the software can be adapted for use in a wide variety of applications, including aerospace satellites, automobiles, scientific research, marine charting systems, and medical devices.

Benefits

- Integrates more than 250 billion pieces of terrain information into a single map
- Images are 1,000 times more detailed with two to three times more fidelity than current aircraft mapping systems
- Merges any number of digital mapping products to create the best available global map
- Applicable to existing aircraft systems, offering industry standard C, C++ code base and map formats

Applications

- Military and civil aeronautics
- Global positioning systems
- Geographical predication and planning
- Earth science data collection

Glenn

Composites for Extreme Environments

Lightweight, high-performance silicon carbide fiber composite materials

Innovators at Glenn Research Center have conducted leading-edge research toward the development of silicon carbide (SiC) fibers and ceramic matrix composites (CMCs) that can be used in high-temperature structural applications, such as hot components in gas turbine engines. Glenn has gained recognition for the innovative design and processing technologies required for these materials.

NASA's patented SiC CMC technologies yield materials that can withstand adverse structural and environmental conditions for long times at temperatures up to 2,700 degrees Fahrenheit. The CMC properties offer significant benefits compared to other options, including metallic superalloys, monolithic ceramics, carbon fiber composites, and oxide/oxide ceramic composites. These composites are also invaluable in their ability to be engineered for specific stress, temperature, life, and environmental conditions.

Benefits

- Lower density, higher temperature capability, and lower thermal expansion compared to metal alloys
- Higher toughness and better damage tolerance than ceramics.
- More predictable life and lower permeability than carbon fiber.
- Greater strength, higher temperature capability, better thermal conductivity than oxide/oxide ceramic composites

Applications

- Heat exchangers, reformers, reactors, and filters for the chemical industry
- Preheaters, recuperators, and radiant tubes for the heat transfer industry
- Thermal protection systems, thruster nozzles, reusable rocket nozzles, and turbopump components for space vehicles
- Nuclear fission and fusion reactors as fuel cladding and radiation blankets

Benefits

- Fuel efficiency
- Reduced mass
- Robust propulsion
- Long life

Applications

- Satellite mobility
- Space cargo transport
- Space exploration

Sun-Powered Propulsion

Small Solar Electric Propulsion Technologies

Glenn has expertise in small solar electric propulsion (SEP). Low-power, high-throughput SEP dramatically increases the capability of small spacecraft, and advanced magnetic circuit design results in game-changing thruster performance. These advances can maximize reliability and minimize cost. Glenn can provide this expertise to U.S. companies through a free, non-exclusive license agreement and companion Space Act Agreement.

This license includes a comprehensive package of design and process documents such as: issued and pending patents, design drawings, materials specifications, vendor lists, software, and test data. Licensees will assist in defining system requirements and creating new platforms to use SEP. This streamlined commercialization strategy aims to improve U.S. competitiveness in the global electric propulsion market.

Goddard

Benefits

- Fuses spaceflight hardware and software to provide a real-time pose estimate for non-cooperative targets
- Operates reliably in a space environment
- Can be adapted to any physical object

Applications

- Spacecraft servicing rendezvous and docking
- Space junk removal
- High-accuracy, real-time relative navigation
- Remotely operated terrestrial vehicles

Staying Aligned at Orbital Speeds

FlashPose relative navigation to enable autonomous rendezvous and capture of spaceborne targets

Goddard Space Flight Center has developed FlashPose, a relative navigation measurement software, for spaceflight missions requiring vehicle-relative and terrain-relative navigation and control. FlashPose processes real-time or recorded range and intensity images from 3D imaging sensors such as laser range finders, and compares them to known models of the target surfaces to output the position and orientation of the known target relative to the sensor coordinate frame.

FlashPose provides a relative navigation, or pose estimation, and capability to enable autonomous rendezvous and capture of non-cooperative spaceborne targets.

Using the Power Grid for Geophysical Imaging

Turns the power grid into an extremely large space science instrument

Goddard Space Flight Center, with the support of the U.S. electric transmission industry, has developed a system that provides real-time data about geomagnetically induced currents (GICs) that flow in power grids during space weather storms. These currents can be a hazard to reliable transmission of electricity. In addition to monitoring GICs for hazard mitigation, this technology also enables the grid to serve as an antenna to study space weather phenomena.

The system extracts information from the grid about continental-scale geoelectric fields and ionospheric and magnetospheric electric currents. These are used to build unprecedented spatiotemporal pictures of near-space physical phenomena. Power system operators can use the real-time data for situational awareness about GICs. This information can guide mitigation actions that power companies may take.

Benefits

- Uses the existing grid to perform large-scale measurements
- Low-cost autonomous design of the magnetometer stations

Applications

- Scientific study of space weather
- Monitoring of the electrical grid for potentially damaging GIC events

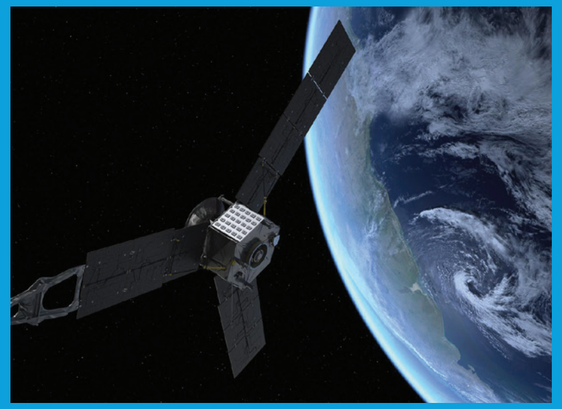
JPL

Mission Development Software

Mission Analysis, Operations, and Navigation Toolkit Environment

Monte, a state-of-the-art Python library, is JPL's signature astrodynamic computing platform, supporting all phases of space mission development from early design and analysis through flight navigation services. With over a decade of use on NASA's most demanding deep-space robotic missions, Monte provides a platform on which users can build their own custom aerospace tools.

It supplies the basic infrastructure – trajectory models, coordinate frames, high-precision time, astrodynamic event searches, sensitivity analysis, numerical integrators, optimization, and more – allowing the user to focus on the problem at hand. All this capability comes with extensive hyperlinked documentation, from introductory tutorials to low-level mathematical details.



Benefits

- Serves as a platform for creating custom applications
- Has an array of tools for trajectory design and space mission analysis and visualization
- Has world-class orbit determination and flight path control libraries

Applications

- Astrodynamic data management
- Trajectory and coordinate frame representation
- Trajectory optimization
- Flight navigation

Benefits

- Capable of multi-vehicle coordination
- Can resolve competing goals
- Narrows the set of solutions to quickly arrive at decisions
- Re-plans in the face of the unexpected

Applications

- Defense
- Disaster response
- Exploration
- Transportation

Architecture for Robotic Planning, Cooperation, and Reaction

Software enables autonomous robotic vehicles and robotic groups

Control Architecture for Robotic Agent Command and Sensing (CARACaS) can enable autonomy in vehicles and groups of vehicles, including aircraft, spacecraft, ground vehicles, and surface water or underwater vessels. The software architecture includes a planning engine, a behavior engine, and a perception engine, with the perception and planning engines coupled to a stored world model. CARACaS can make plans and change them according to changing goals, circumstances, or resources. All behaviors cooperate to resolve complex or even conflicting goals within the constraints of the mission.

The Navy has funded CARACaS to serve as the autonomy backbone of several unmanned maritime systems and recently funded advances to improve the technology's situational awareness, safe navigation, and mission operation, enabling more complex, more autonomous missions.

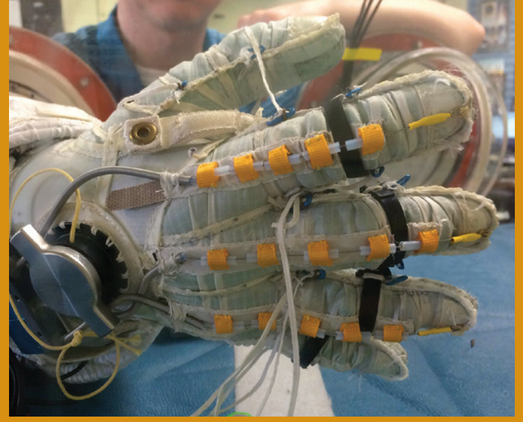
Johnson

New Capabilities for Grasp-Assisting Gloves

Spacesuit robotic glove

Researchers at Johnson Space Center have designed and developed spacesuit gloves with grasping and restorative capabilities to increase both strength and mobility. These new capabilities comprise components that can be integrated into existing grasping gloves to enhance operation and range of motions. In particular, actuators were designed to have a greater force output, better efficiency, and higher reliability and thermal range than commercially available actuators. Also, position sensors were added to improve the accuracy of the grasping motion, as was a built-in restorative force to assist movement back into a relaxed, non-grasping position.

A "triple brummel anchor" was designed to improve the interaction between the actuator and a human finger to prevent cinching and avoid high stress concentrations in the line of the "tendon" used to maneuver the wearer's hand while performing tasks. The anchor can be integrated outside the glove and requires no special tools. Industries such as manufacturing and healthcare can benefit from these components.



Benefits

- Enhances robotic systems: can easily be integrated to enhance an existing grasp-assist glove
- Improved actuators: greater force output, better efficiency, higher reliability and thermal range
- Position sensors: improved locational movement for better grasping assistance
- Triple brummel anchor: soft material anchors the glove to a hand firmly but without stress or pain

Applications

- Healthcare: development of rehabilitation aids and assistance of patients with impaired hand strength
- Manufacturing: operation of tools and performance of manual labor for extended periods

Precision Low-Speed Motor Controller

Inexpensive low-speed brushless DC motor controller

Innovators at Johnson Space Center have developed a method for controlling precise motion of a brushless DC motor using relatively inexpensive components. Precision motors are usually quite expensive and inefficient when operating at slow speeds. This technology uses a method to control these motors over a broad range of speeds, ranging from about 0.025 rpm to about 7,000 rpm.

Its ability to operate at these ranges with high precision provides an opportunity to integrate this technology into many applications and industries. Commercial motors may employ this technology to extend their dynamic range. It can also be integrated into surgical robots that require advanced precision motion-control systems. Hybrid and electrical vehicles can integrate this technology into their operating systems to improve efficiencies.

Benefits

- Precise in low-speed motion: smooth enough to be applied to surgical robots
- Efficient: reduces noise associated with slow-motion operations
- Inexpensive: able to perform same functions as more-expensive motors

Applications

- Robotic systems: precision low-speed motion
- Motor industry: extension of the dynamic range
- Automotive industry: reduction of sensor noise on the system

Kennedy

Cryogenic Flux Capacitor

A device for solid-state storage and on-demand distribution of cryogenic fluid commodities

Kennedy Space Center's cryogenic flux capacitor (CFC) capitalizes on the energy storage capacity of liquefied gases. By exploiting a unique attribute of nano-porous materials – aerogel in this case – fluid commodities such as oxygen, hydrogen, and methane can be stored in a molecular surface-adsorbed state. This cryogenic fluid can be stored at low to moderate pressure densities, on par with liquid, and then quickly converted to gas when the need arises.

This solution reduces both safety-related logistical issues and the limitations of complex storage systems. Currently, high-pressured gases are stored in vessels with heavy, thick walls that require constant pressurization and complex storage systems to limit boil-off. These systems are not well suited to dynamic situations where the tank orientation can change suddenly. NASA's CFC addresses all these issues, simplifying current operations and opening the possibilities for new applications and new markets for cryogenic liquid.

Benefits

- Compact fuel storage
- Lightweight
- Low to moderate storage pressures
- Fast charge-up times

Applications

- Spacecraft
- Transportation
- Fuel cells
- Medical applications

Passive Porous Tube Irrigation System

System autonomously supplies water and nutrients to plants

The Passive Porous Tube Nutrient Delivery System is a plant growth technique that delivers a nutrient solution to the roots of plants via capillary action. The system was originally designed for use in microgravity. It uses a ceramic porous tube and water-filled nutrient bags connected in a loop. No electricity or moving parts are required. Instead, the nutrients are pumped in through a combination of capillary force and evapotranspiration from the plant. The porous tube supplies the plants with the water and nutrients needed to germinate and grow.

This system provides an autonomous plant growth apparatus that is simple to assemble, plant, and harvest, minimizing the amount of intervention needed.

Benefits

- Minimizes labor involved in plant growth
- Delivers only what plants need
- Ensures against over- or under-watering
- No electricity or moving parts

Applications

- Vertical farming
- Green walls

Langley

More Precise Positioning

Improving Global Positioning System accuracy for internet-capable mobile devices

One factor limiting the possible uses of GPS-enabled devices, such as establishing drop zones for package delivery, is that these devices typically have limited precision positioning capabilities. This system is designed to work with any internet-enabled mobile device that has access to its GPS pseudorange, code phase, and, potentially, carrier phase measurements.

The system uses GPS measurements or corrections from a stationary base station to refine its positioning estimate using established computational techniques such as those associated with differential GPS, Real-Time Kinematic GPS and/or the Local Area Augmentation System. These remove errors common to the measurements of both devices (mobile and base station), increasing the accuracy of position estimates.

Benefits

- Supports one-meter positional accuracy
- May be independent of existing Networked Transport of RTCM via Internet Protocol systems
- May be operational in areas outside of existing systems

Applications

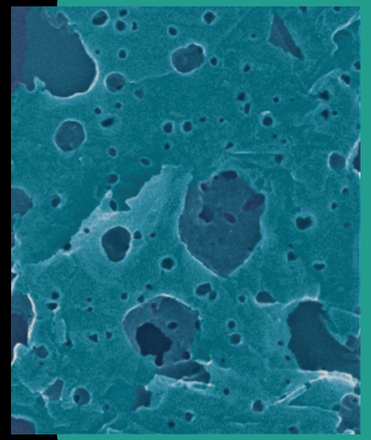
- Using mobile devices to mark a location, such as for drone-based package delivery
- Accurate GPS location of 911 callers for first responders

Holey Carbon Allotropes

Innovative manufacturing methods for bulk preparation of holey graphene and holey carbon nanotubes

Scientists at Langley Research Center have developed new methods to manufacture carbon materials such as nanotubes and graphene with holes through the graphitic surface of the particles. The methods generate materials with increased accessible surface area, increased functional groups at damage sites, and improved through-surface molecular transport properties.

The materials generated using these techniques are anticipated to be applicable to a variety of industries, especially energy storage, such as supercapacitors and batteries, and separation membranes for gas, ions, organics, proteins, and more.



Benefits

- Produces carbon nanomaterials with increased surface area, improved electrochemical performance, and through-surface molecular transport properties
- Eliminates need for catalysts, solvents, and flammable gases for processing
- Allows for control of material properties such as surface area, modulus, thermal conductivity, and thermopower
- Is readily scalable and can be used to generate bulk quantities, only dependent on the availability and cost of pristine materials

Applications

- Energy storage and generation (supercapacitors, batteries)
- Membranes for gas separation, water desalination, biomolecular separation
- Gas and drug delivery
- Chemical and biological sensors

Marshall

High-Flow Cleaning

Clean complex additively manufactured parts in minutes, not hours or days

Powder-based additive manufacturing methods typically require post-fabrication component cleaning to remove residue powder from the surface and crevices of the part, a task that becomes increasingly difficult and time-consuming with part complexity. This invention uses a large volume of pressurized air to quickly enter a cleaning chamber. Based on the Bernoulli principle and continuity equation, the high flow results in significant air velocity and a decrease in pressure when airflow passes through smaller component orifices, which in turn removes remnant powder from the part.

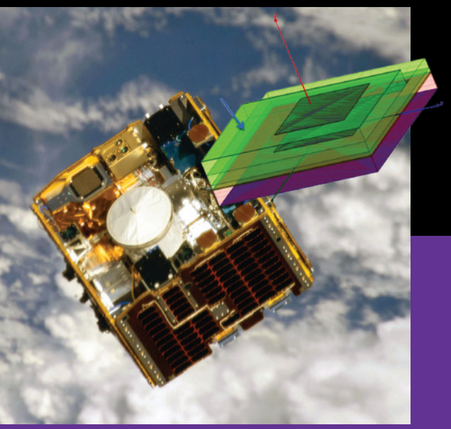
The technology can be implemented as a stand-alone cleaning system for powder bed-fusion additively manufactured parts or could be integrated into a packaged post-processing system offering. CT scans of complex NASA parts cleaned using a proof-of-concept system revealed promising results. NASA welcomes industry to test the technology under an evaluation license.

Benefits

- Fast, automated process: parts are cleaned in minutes, instead of hours or days
- Effective cleaning: CT-scans of cleaned parts revealed effective particle removal
- Works on complex parts: removes remnant powder lodged in small channels and passageways found in complex additively manufactured parts

Applications

- Powder-based additive manufacturing, including direct metal laser sintering, electron beam melting, selective heat sintering, selective laser melting, and selective laser sintering
- Post-processing of complex additively manufactured parts



Versatile Broadband Antenna

Novel design provides broadband on multiple bands with high signal gain

Researchers at Marshall Space Flight Center have developed a novel patch antenna technology. This simple antenna design provides significant benefits to satellite communication applications, offering a unique wideband/multiband operating capability. The antenna design also offers broadband capability with high gain for commercial space or non-space applications where signal strength and smaller antenna sizes are important. The technology was developed to address the need for satellite antennas whose target communication frequency is unknown or unassigned.

Benefits

- Wideband operation across multiple frequency bands, with high-gain signal strength and hemispherical coverage
- Flexibility in antenna design where communication frequencies within a particular band have not been assigned
- Small, thin, and easily manufactured in a simple, multilayer device
- Prototypes have been validated in operational environments

Applications

- Satellite and terrestrial communications where wide-band operational capability across multiple frequency bands is needed, including situations where the antenna design precedes the allocation of communication frequency

Stennis

Floating Piston Valve

Novel approach to low-maintenance, actuator-less valves

The valve consists of a solid piston floating in a medium to control the flow stream. The piston is designed to be axially and radially balanced within the flow stream whether the valve is in the open or closed position. The only force imparted onto the piston is that which the operator chooses to put on it. This eliminates a conventional actuator (replaced by one or two simple solenoid valves) as well as valve actuator adjustments. It also eliminates the valve stem and stem seals and most flow-induced thrust forces, and ensures consistent seating force regardless of the pressure drop across the valve.

The simple design allows for use in nominal or extremely high pressures and for the use of soft or hard metal seats; this valve design reduces downtime and maintenance costs while increasing valve reliability and seat life.

Benefits

- Reduced maintenance due to single design with fewer parts and seals
- Reduced size and costs
- Hermetically sealed and leak-free
- Withstands high pressure

Applications

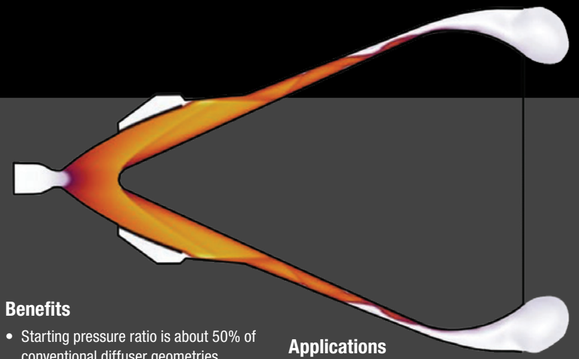
- Power plants
- Chemical industry and refineries
- Cryogenic fluid systems
- Pharmaceutical manufacturing industry

Supersonic Spike Diffuser

Double the pumping efficiency in one quarter the space

Conventional cylindrical and second-throat supersonic diffuser designs allow the plume from a de Laval nozzle to fill its cross-section without centerline obstruction. This allows a vacuum to be created within any void upstream of plume impingement, but it does so inefficiently due to shock losses at high Mach numbers. Centerbody diffusers provide an improvement by reducing the maximum Mach number but also increase the number of oblique shocks by turning the flow multiple times.

Spike diffusers harness the best attributes of each and provide approximately double the pumping performance through Pareto-efficient reduction of both Mach number and flow deflection. Because spike diffusers can start at half the pressure ratio of conventional diffusers, much lower pumping pressures can be achieved for a given feed pressure by using larger expansion-ratio de Laval nozzles. Spike diffusers are also compact, requiring a length of only about 20 to 30% of that of conventional designs.



Benefits

- Starting pressure ratio is about 50% of conventional diffuser geometries
- Lower vacuum achievable for the same feed pressure
- Compact
- Reduced structural overhead

Applications

- Steel production
- Chemical processing
- Oil refinement
- Flavors and fragrances (vacuum distillation)

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