

National Aeronautics and Space Administration



SPINOFF

2022

On the cover

NASA-NOAA's Suomi NPP satellite captured an image of phytoplankton and smoke from fires as it passed over Australia's Cape Barren Island. This natural-color satellite image from Dec. 7, 2016, was collected by the Visible Infrared Imaging Radiometer Suite instrument. Chlorophyll gives the phytoplankton (microscopic plant-like organisms) their green color, which is visible from space when large numbers of the organism group together.

Weeks after a successful hot fire test at NASA's Stennis Space Center in March 2021, team members worked to remove the first core stage of the agency's Space Launch System (SLS) rocket from the test stand. This marked the completion of the "green run" series of eight tests over the past year. The rocket was then transported to Kennedy Space Center, to prepare for launch of the Artemis I mission.

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MAIN ENTRANCE

SPINOFF

2022

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Contents

1 Introduction

3 Spinoff Capsules

25 Spinoff Features

26 A Moveable Feast: Plant Research for Space Advances Earth Agriculture

The need to generate oxygen and grow food in space inspired NASA to test indoor agriculture techniques. Thanks to agency-funded research, private companies are building on NASA's vertical farm structure, plant-growth "recipes," and environmental-control data to create successful indoor farms.

30 NASA Helps Private Lander Shoot for the Moon

A company leveraged NASA expertise to develop one of the first commercial lunar landers, which will deliver agency science and technology payloads to the Moon in 2022. Private organizations and individuals are also sending payloads as space exploration becomes more accessible to everyone.

34 NASA Helps Drones Take Flight

NASA research and funding have helped lay the foundations for a variety of remotely piloted and autonomous aircraft to play a much bigger role in our lives, with small drones likely delivering packages and even takeout one day, and larger, jet-sized drones inspecting cellphone towers and other infrastructure, among other tasks.

40 Space Pens, Pencils, and How NASA Takes Notes in Space

In the 1960s, a pen company accelerated development of a pressurized ballpoint to meet NASA's need for a pen that could write in zero gravity. NASA tested the resulting pen rigorously. The Space Pen has flown on every crewed mission since Apollo 7 and become a popular gift item on Earth.

42 Forecasting Saharan Dust to Minimize Health Risks

NASA-funded researchers at the University of Puerto Rico use satellite data to track dust and other aerosols traveling across the Atlantic Ocean from the Sahara Desert. They alert local and federal governments and the public in advance of poor air quality.

44 NASA's Robotic Glove Finds Commercial Handhold

NASA and General Motors joined forces to build Robonaut 2. The work led to a suite of robotic glove patents, now licensed and commercialized for industrial workplaces.

48 Safely Detoxifying Soil and Groundwater with NASA Technology

The chemicals used to clean rocket parts in the 1960s posed a threat to a wildlife refuge next to NASA's Kennedy Space Center, inspiring an eco-friendly cleanup solution that's now decontaminating sand, soil, fractured bedrock, and groundwater around the world.

51 Expertise Flows from Computer Cognition

Artificial intelligence systems to monitor performance of space systems and suggest solutions to issues led one company to use software derived from those programs in energy production across the entire process.

54 Lasers Make Waves in Self-Driving Cars, Quantum Devices

The optoelectronic oscillator and whispering gallery mode optical resonator, created at NASA and licensed to their inventor, have gained widespread popularity and enable high-performance lasers and communication devices for emerging fields.

56 Lighting in a Bottle

Many companies have benefited from NASA-funded lighting research and development aimed at growing plants in spacecraft and helping astronauts adjust to space travel. Products based on these technologies help people feel more energetic during the day, decontaminate rooms, and boost indoor agriculture production.

60 Clean Air Tech for Spacecraft Helps Fight Pandemic

Companies had already commercialized technologies developed for scrubbing the air in spaceborne plant-growth chambers and sensing air quality in spacecraft. After it became clear that the novel coronavirus was transmitted through the air, demand for products based on these technologies skyrocketed.

64 'Reflecting' on Life's Daily Challenges

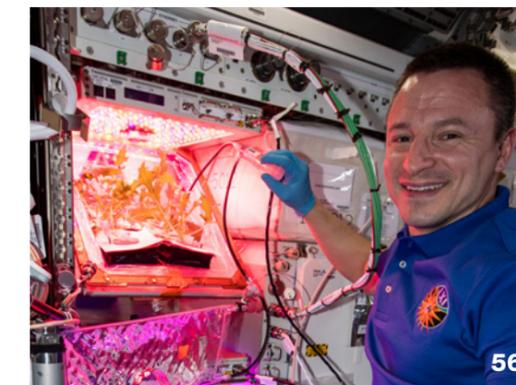
Inspired by the "space blankets" at her first post-surgery race, one runner turned a fabric based on NASA's radiant barrier insulation into a line of warm, lightweight, weatherproof jackets.

66 Spinoff Technology Across the Nation

68 Technology Transfer Program

70 Improving the Ways NASA Brings Technology Down to Earth

74 Spinoffs of Tomorrow



Spinoff (spin'ôf) -noun.

1. A commercialized product or service 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 former 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.

This Space Launch System rocket configuration, seen here at night on the mobile launcher, includes the Exploration Upper Stage that will provide in-space propulsion to send astronauts in NASA's Orion spacecraft and heavy cargo on a precise trajectory to the Moon. Manufacturing both the core stage and Exploration Upper Stage is a collaborative effort between NASA and Boeing. Under the Artemis program, NASA is working to land the first woman and the first person of color on the Moon to pave the way for sustainable exploration of the Moon and future missions to Mars.



Introduction

Welcome to the latest edition of *Spinoff*!

This has been a year like no other. Our country faced unprecedented challenges in the face of the novel coronavirus pandemic but also developed the means to re-emerge in safety and health. This is thanks in large part to the miracle of technology and science, most notably, of course, in the form of multiple highly effective vaccines.

However, the fight against the virus that causes COVID-19 has been fought on multiple fronts. We are proud that NASA technology – both technology originally conceived for space exploration as well as technology designed specifically for this crisis using our deep bench of engineering expertise – has played even a small role in reducing transmission and caring for the ill, not just in the United States but around the world.

Last year, we shared how our engineers at the Jet Propulsion Laboratory sprang into action at the start of the pandemic to design an innovative ventilator that doesn't use any of the same parts as traditional devices. While I wish it had never been needed, I am glad to report that when India faced some of the most dire moments of this worldwide tragedy, NASA's new ventilator was available to supplement the vital equipment in overtaxed intensive care units (page 70).

Technology NASA has helped fund and develop over decades to keep air fresh in spacecraft has also been pulled into service. Air purifiers that use photocatalytic oxidation to supplement traditional HVAC filtration have been shown to eliminate virus particles in indoor air, and an air-quality sensor tested on the space station helps determine the risk of airborne virus spread in an indoor space (page 60).

But NASA's dedication to exploring and understanding Earth, the solar system, and beyond never stopped. And neither did the work of our Technology Transfer program, the single longest continuous mission of our agency. That work has paid off in countless ways, and this year in *Spinoff*, we highlight dozens of great new examples.

Here are some of my favorites:

- NASA pioneered the first-ever indoor, vertical farm in the United States – an effort to better understand how to use plants to keep astronauts fed and healthy on long-duration flights. Today, numerous companies are learning from our example, using our technology and techniques to grow food for Earth's burgeoning population with a far smaller environmental footprint (page 26).
- Kennedy Space Center, besides being the site of our most historic launches, is also located in one of the largest and most diverse wildlife preserves in Florida. Some of those early launches took an environmental toll we didn't learn about until later. Seeking to mitigate the damage, a Kennedy engineer devised an innovative cleanup technology, which now helps relieve polluted environments around the world (page 48).
- Robots are crucial to our efforts to explore space and other planets – they support astronauts and can form the advance party for places humans have yet to reach. But the human machine is hard to replicate. A collaboration with industry helped us design a better robotic hand – and the effort has been adapted into a robotic glove that helps manufacturing workers reduce injuries (page 44).

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 75).

Our mandate is to ensure NASA technology benefits the widest possible population. We are proud to present *Spinoff 2022* to show the many important ways there's more space in your life than you think.



Jim Reuter
Associate Administrator
Space Technology Mission Directorate
NASA Headquarters

American, Japanese, and European astronauts participated in an October 2020 exercise simulating an emergency situation after splashdown of the Crew Dragon spacecraft. Using a mock-up of the Crew Dragon, the astronauts practiced exiting the capsule and jumping into the water. The crew successfully launched together to the International Space Station from Kennedy Space Center on April 23, 2021.



SPINOFF Capsules

Since the early days of the Space Race, NASA engineers and scientists have been developing technology to help us explore the universe and understand its workings. These efforts, as always, pay off in all kinds of ways for everyone on the ground. Read on for a quick glance at technology we built or funded that has been adapted to benefit all of us.

Measuring Moon Dust to Fight Air Pollution

NASA's need to contain hazardous lunar dust led to technology that senses other pollutants

Moon dust isn't like the stuff that collects on furniture – it's ubiquitous and abrasive, and it clings to everything. It's so bad that it even broke the vacuum NASA designed to clean the Moon dust off Apollo spacesuits. Apollo astronaut Harrison Schmitt described his reaction to breathing the dust as "lunar hay fever," including sneezing, watery eyes, and a sore throat.

With NASA's return to the Moon, dealing with the dust is critical. Concern for human health is a driving force behind NASA's research into all forms of lunar soil, called regolith. The first step is knowing how much is in the air, and efforts to do just that are already paying off on Earth in the fight against air pollution.

While air filtration can remove many of the tiny particles, an air-quality sensor ensures the controls are effective. This was one focus of NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) program. The agency invited private industry to help overcome obstacles to future lunar missions.

Lunar Outpost Inc., which aims to develop technologies for lunar exploration and then adapt them for use on Earth, responded with the Space Canary. The Denver-based company developed the air-quality sensor and offered the technology to Lockheed Martin Space, a frequent NASA partner. Lockheed had successfully bid on a NextSTEP public-private partnership to build lunar orbit habitat prototypes for testing at NASA's Kennedy Space Center in Florida, and the company brought Lunar Outpost on as a contributor to tweak its Space Canary system to meet NASA's needs. The device exceeded requirements for the habitat prototype.

Rebranded Canary-S (Solar), the sensor is now filling a need for low-cost, wireless air-quality and meteorological monitoring on this planet.

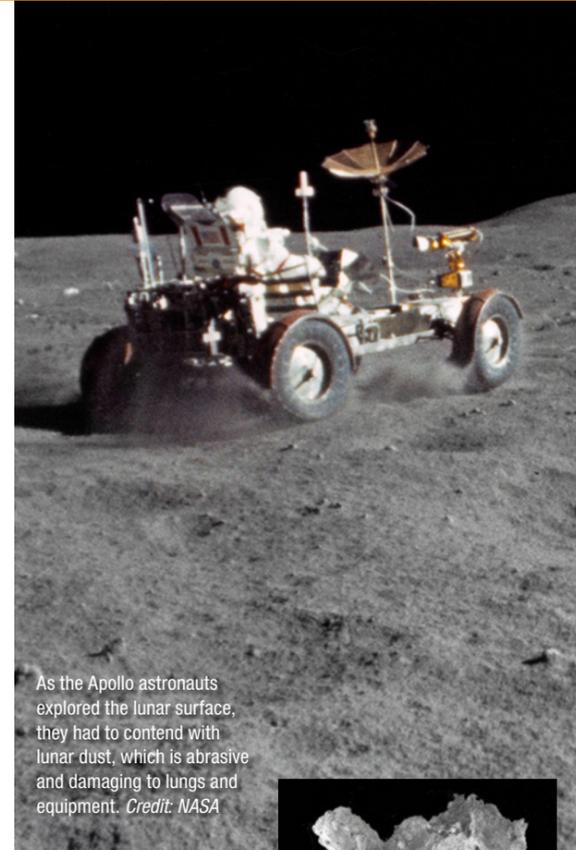
Particulate matter is a form of air pollution generated by forest fires, volcanic eruptions, and burning fossil fuels that consists of particles much smaller than a grain of sand. These cause myriad health problems including respiratory and cardiovascular conditions. Particulate matter also contributes to numerous environmental issues, including climate change.

The Canary-S is a self-contained unit that continually takes measurements and transmits data using cellular technology. It can measure a variety of pollutants, including particulate matter, carbon monoxide, methane, sulfur dioxide, and volatile organic compounds. Messages are sent to a secure cloud every minute, where data is available for viewing and analysis.

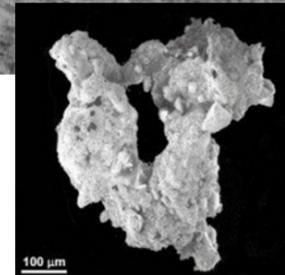
A recent study by the Payne Institute for Public Policy of the Colorado School of Mines provided independent verification of the Canary S sensor's accuracy for daily and long-term measurements.

The sensor is now deployed in 15 states and across numerous industries. The U.S. Forest Service, for example, is using it to monitor forest-fire emissions in real time. When carbon monoxide levels are high, a warning alerts firefighters to take necessary precautions.

The city of Denver chose the Canary to collect data at local schools to educate teachers, parents, and students about their local air quality. And in the oil and gas industry, the sensor helps provide evidence of environmental control efficacy by providing continuous, real-time monitoring of fugitive gas emissions. ●



As the Apollo astronauts explored the lunar surface, they had to contend with lunar dust, which is abrasive and damaging to lungs and equipment. Credit: NASA



Lunar dust, the finest type of lunar soil, is similar in composition to lava rocks on Earth. It is formed when micrometeorites collide with the Moon. Enough energy is released to melt the surface rocks into a glass-like substance, which cools into tiny flecks. Credit: NASA



Ahead of future lunar missions, NASA wanted a sensor to act like a canary in a coal mine, warning inhabitants if the level of dust gets dangerous. Lunar Outpost developed the Space Canary, an air-quality sensor, shown here in a lunar habitat prototype designed by Lockheed Martin. Credit: Lockheed Martin Corporation

Microbes Help Trees Clean Up Pollution

Bacteria-fortified trees now eliminating pollution were first field-proven with help from NASA

NASA explores outer space, but it's also owner and steward of hundreds of square miles of planet Earth. The scientists and engineers at the space agency's field centers have tried various methods to preserve the land they work on, and several of these have found use around the rest of the planet.

The latest, first field-tested at Ames Research Center in Silicon Valley, California, is now in practice at about 30 environmental remediation sites around the country.

Around 2012, Dr. John Freeman of engineering and biosciences company Intrinsic Technologies was leading space station seedling growth experiments and other work for Ames' Space Biosciences Division. With a background that included phytoremediation – using plants to clean up pollution – Freeman also followed the work of a University of Washington professor who had isolated strains of symbiotic bacteria, known as endophytes, that helped trees break down specific common contaminants.

The work showed promise in the laboratory but hadn't been tested in the field.

Ames, meanwhile, had been pumping up and treating contaminated groundwater flowing under the center from the site of a former computer chip manufacturer next door. Freeman approached the center's Environmental Management Division with an alternate solution – hundreds of poplar trees inoculated with a strain of bacteria known as PDN3, which feeds on trichloroethylene (TCE). This is the main groundwater contaminant at Ames and is also common at environmental cleanup sites around the world.

Ames personnel, contractors, and interns helped select the best location, plant and irrigate the trees, and maintain the plot. As the roots reached the water table in 2016, Ames installed test wells at each end of the grove and tested groundwater before it flowed into the grove and after it flowed out.

The results were decisive. Samples from the well where contaminants entered the grove contained TCE at concentrations around 300 parts per billion (ppb), but concentrations in the outflowing water were below the drinking water standard of 5 ppb. And while the inoculated trees were healthy and green and contained barely detectable levels of TCE, many of the uninoculated trees planted among them as a control group were stunted and yellow, and they had concentrations of TCE almost as high as the contaminated groundwater.

With these results in hand, Intrinsic started a new division, Intrinsic Environmental, also located at Ames in Moffett Field, California, which took over the project. The center became its first customer, purchasing another 500 inoculated trees in 2017.

Intrinsic Environmental now has stands of poplars, willows, and other trees inoculated with endophyte bacteria that consume TCE and petroleum products at dozens of sites around the country. The Arbor Day Foundation is working with Intrinsic to get more endophyte-enhanced trees in the ground for phytoremediation.

"It's one thing to know it works in a greenhouse or petri dish, but how's it going to perform inside a tree in the field?" asked Freeman. "And now, thanks in part to our collaboration with NASA, we know the answer." ●



In 2014, one year after planting at Ames Research Center, the rows of poplars inoculated with microbes to help them break down a contaminant present in the groundwater are noticeably larger, greener, and healthier than the rows of uninoculated trees forming the control group. Credit: Intrinsic Environmental



The first grove of inoculated poplars and uninoculated control trees was planted between two baseball fields at Ames. As the trees took root, center personnel installed a test well at each end of the plot to compare contaminant levels in groundwater flowing into the grove against water coming out. The results were so dramatic that the center purchased two more stands of inoculated poplars, seen here just south of each baseball field. Credit: Google Earth

Pounding Metal Parts into Profit

A novel additive manufacturing technique combines metals and embeds sensors

A burst water main is always a mess, but a pipe that fails in space can be mission-ending. That's why NASA technologists must make hardware as reliable as possible.

This challenge spurred Scott Roberts, a technologist at NASA's Jet Propulsion Laboratory in Southern California, to turn to a new kind of welding in the 3D printing industry. He thought ultrasonic additive manufacturing could improve spacecraft components' reliability. Now one company that used the technique to build parts for Roberts is manufacturing parts for industries from aeronautics to oil drilling.

What does 3D printing have to do with pipes? Temperature is a problem in space, where extremes vary by hundreds of degrees. Heat exchangers help spacecraft maintain a steady temperature by removing excess heat or drawing in more. They normally have many parts, introducing numerous potential points of failure. Small Business Innovation Research (SBIR) funding from JPL let Columbus, Ohio-based Fabrisonic LLC take a new approach to building a heat exchanger. The company started with its existing process, which uses high-frequency vibrations to fuse together multiple thin layers of metal. To create the heat exchanger, a curved channel was carved into the layered metal and then enclosed under additional layers.

How can vibrations fuse metal? Ultrasonic welding uses constant pressure and ultrasonic vibrations to cause friction between layers of metal, raising temperatures and removing surface oxides to allow direct contact between surfaces. The result is an atomic bond that welds the layers together. Even different metals can be bonded together. Ultrasonically manufactured pieces can be as large as six feet square, have complex geometries, and be produced in a matter of days, not months.

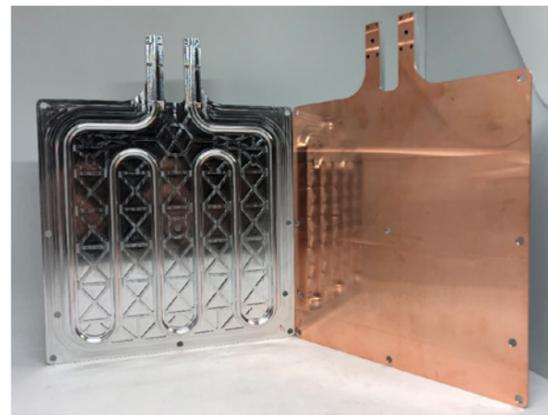
Why combine different metals? Protecting electronic components from space radiation that can destroy them is challenging when everything on a spacecraft needs to be lightweight. Additional SBIR funding provided by NASA's Langley Research Center in Hampton, Virginia, paid for Fabrisonic to add layers of radiation-resistant tantalum in the middle of aluminum spacecraft parts. Customers in the oil and gas industry use this process for making well drill pipes – hollow, thin-walled tubing that combines dissimilar materials and uses embedded sensors.

Why put sensors inside metal? Fiber-optic sensors can detect metal strain or weaknesses and predict possible failures. Other SBIR funding from Langley helped Fabrisonic test the effectiveness of sensors built into aluminum parts. The company found that the sensors, protected within metal, can function in harsh environments like the Oak Ridge National Laboratory, which researches energy and nuclear science. In NASA aeronautics testing, the sensors helped detect weaknesses and performance issues in commercial airframes.

What if I want to print small parts myself? SBIR funding from NASA's Marshall Space Flight Center in Huntsville, Alabama, let Fabrisonic explore advanced metals and ultrasonic welding for in-space manufacturing. NASA engineers helped the company create the key component of a small ultrasonic printer – the weld head that transfers vibration onto the device's metal tape. Commercial sales of the resulting SonicLayer 1200 printer have generated \$1 million in revenue, with one customer producing over 70,000 parts. ●



CubeSats can be used for a variety of tasks, from Earth observation to flying science experiments, but their small size makes it a challenge to assemble all the parts as well as shielding needed to manage the extreme temperatures of space. NASA is interested in new manufacturing techniques that enable more efficient use of materials. *Credits: NASA*



This 3D-printed radiator for a CubeSat combines aluminum and a small bit of copper to allow heat to spread more evenly across the face. Fabrisonic was able to combine the metals using additive manufacturing techniques that employ ultrasonic welding. *Credit: Fabrisonic LLC*

Water Purification Anywhere on Earth

Company puts NASA-enhanced filter in consumer water bottles, looks to expand to developing world

Piush Soni didn't think much about clean drinking water until it became hard to find.

As a gemologist spending long periods in African jungles, he realized he wasn't the only one worrying about his next drink of water. "In these countries, you had children dying weekly, drinking from puddles, rivers, and lakes. It's only there that you realize how valuable water really is."

One place where drinking water is even scarcer, however, is space. As Soni researched ways to purify water in the bush, he soon discovered a technology developed with help from NASA. Providing astronauts with clean drinking water has been a challenge since the space agency's earliest days, one that has prompted it to invest in several technologies.

One of these is a filter material called NanoCeram, optimized and tested by Argonide Corporation with the help of two Small Business Innovation Research contracts from NASA's Johnson Space Center in Houston in the early 2000s. The technology has since been incorporated into a host of products by several companies (Spinoff 2004, 2009, 2013, 2017, 2021).

Today, Finnish company Ahlstrom-Munksjö holds an exclusive license from Argonide and sells the material under the brand name Disruptor.

In these filters, positively charged aluminum oxide microfibers attract and capture the tiniest contaminants, most of which have a negative charge, while allowing for a high flow rate.

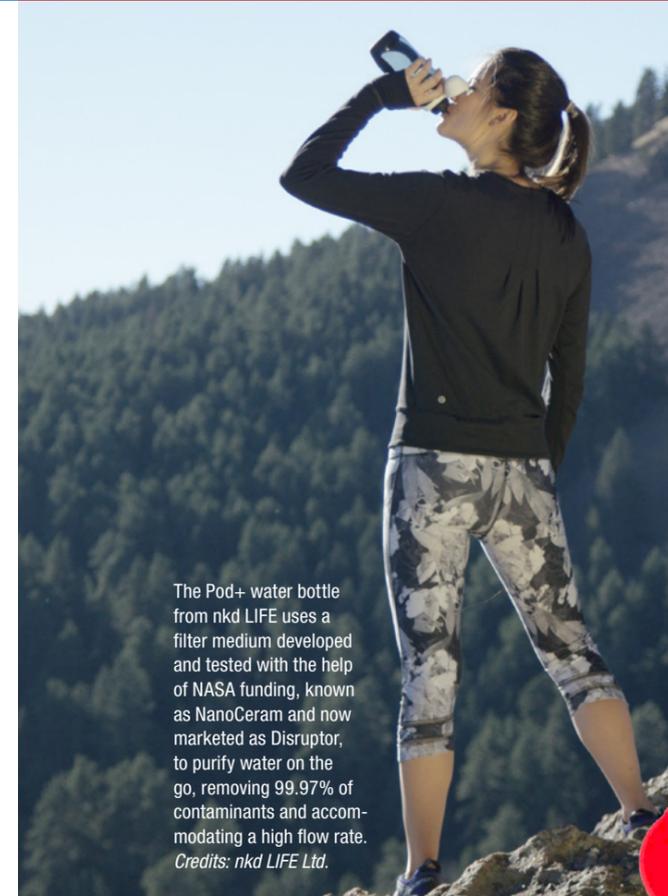
Soni founded nkd LIFE Ltd. in England in 2016 and enlisted an engineer friend to design a bottle using a Disruptor filter to purify water on the go. Within two years, they had the Pod+ water bottle, which purifies water, conditions it to improve taste, and adds ions and antioxidants.

Since its release, nkd LIFE has sold more than 1.5 million Pod+ units and established offices on four continents, including one in West Palm Beach, Florida.

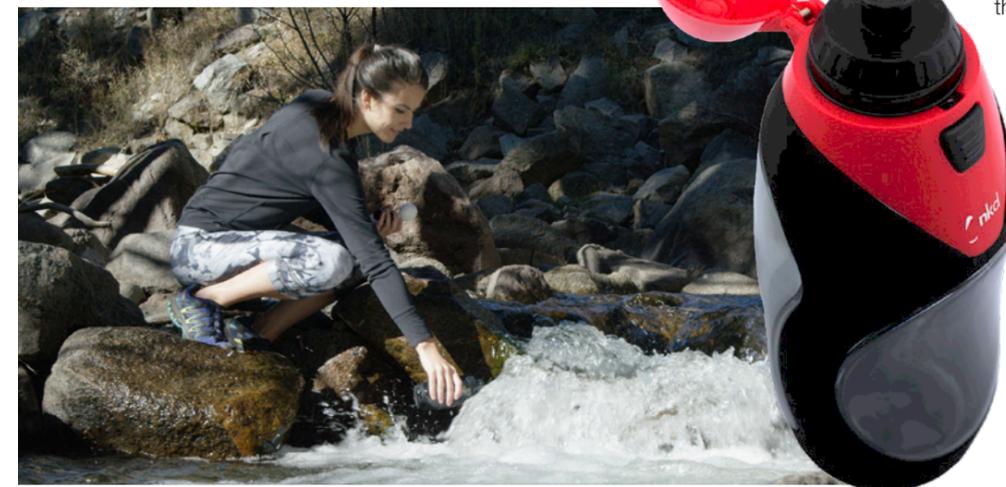
In Europe and North America, the bottles are popular among health-conscious consumers and travelers to areas lacking potable tap water, and as company gifts to employees. In much of Asia and Africa, where tap water isn't safe for drinking, the company has customers in all walks of life. Thanks in part to the filter medium NASA helped fund two decades ago, the Pod+ is less expensive than other options while still removing 99.97% of contaminants and accommodating a high flow rate.

Beyond the consumer market, Soni also wanted to sell the invention to humanitarian organizations for distribution in the developing world. However, it didn't yet meet all of those nonprofits' specifications for low-cost, high-volume filtration that could purify the dirtiest water. "We sort of took that as a challenge," he said.

He founded a second company, iThrive Labs Ltd., to develop a system that could purify large quantities of water from any lake or river. The system will incorporate another NASA-based technology, the Aquaspace filter medium (see page 21), in addition to the Disruptor filters. Called Lifepod, it's planned for distribution in 2022. ●



The Pod+ water bottle from nkd LIFE uses a filter medium developed and tested with the help of NASA funding, known as NanoCeram and now marketed as Disruptor, to purify water on the go, removing 99.97% of contaminants and accommodating a high flow rate. *Credits: nkd LIFE Ltd.*



Helping Solve Climate Challenges

NASA research and innovations have led to more environment-saving spinoffs than we can count. Here are a handful of technologies helping curb greenhouse gas emissions, advance renewable energy technologies, and better understand the processes leading to climate change. For more, visit spinoff.nasa.gov/climate-change.

All-Electric Flight

With NASA's help, a company designed a high-power battery pack that could meet safety requirements for the agency's all-electric experimental airplane. Now the company is selling batteries based on that development for use in some of the first all-electric passenger planes.

Sniffing Out Gas Leaks

A spectrometer created to look for methane on Mars is 1,000 times more sensitive than competing technology. The device can be handheld or mounted on a drone or car and lets natural gas producers easily spot and stop leaks.

Send In the Clones!

A program that creates high-fidelity digital models – or “clones” – of mechanical components or systems was validated against years' worth of NASA helicopter gear data. Now it allows some of the country's largest wind turbine operators predict and extend their turbines' lifespans.



Running on Empty

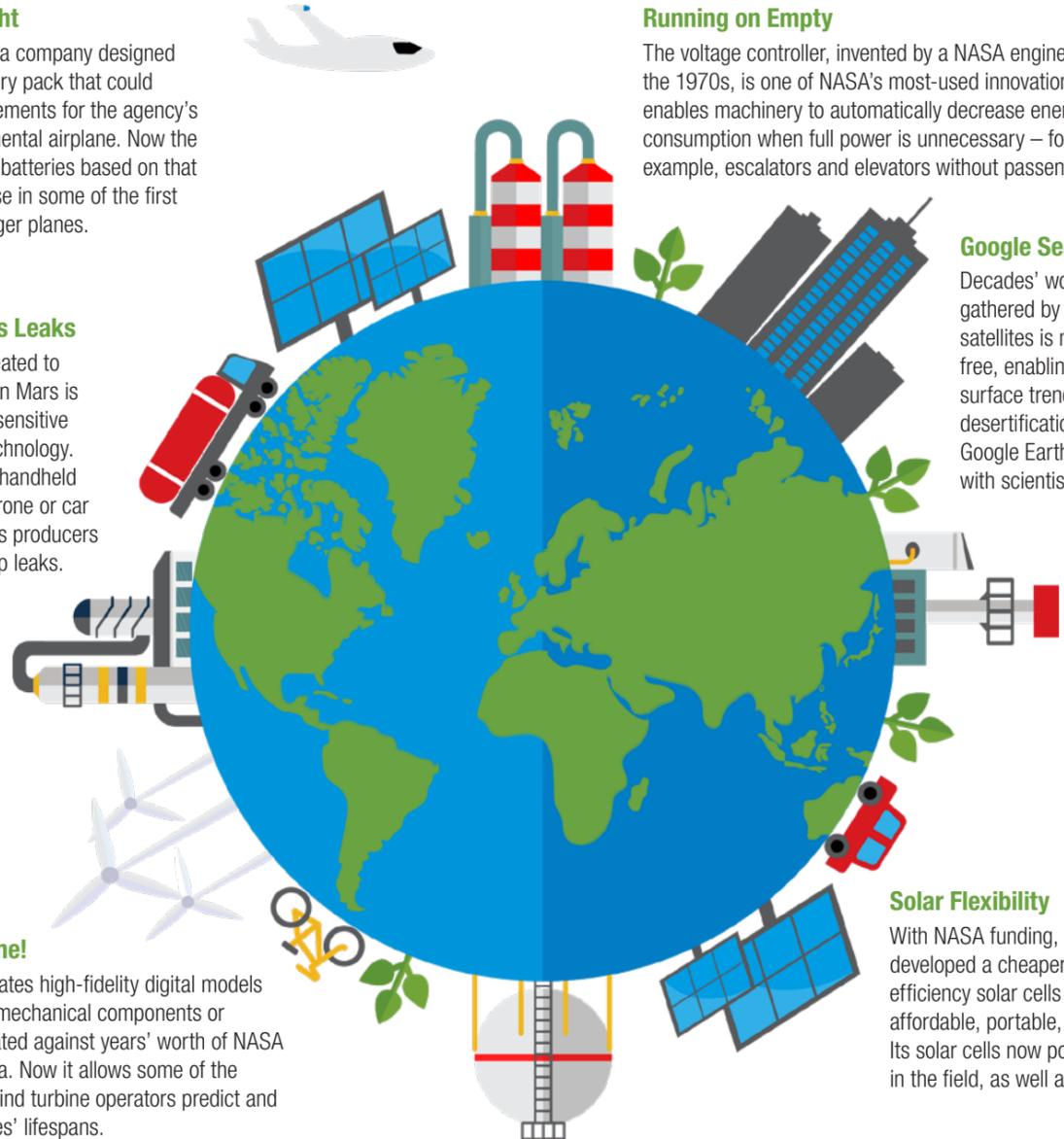
The voltage controller, invented by a NASA engineer in the 1970s, is one of NASA's most-used innovations. It enables machinery to automatically decrease energy consumption when full power is unnecessary – for example, escalators and elevators without passengers.

Google Searches Earth

Decades' worth of Earth imagery gathered by the NASA-built Landsat satellites is now available for free, enabling global analyses of surface trends like glacier retreat, desertification, and deforestation. Google Earth Engine is partnering with scientists to mine all that data.

Solar Flexibility

With NASA funding, one company developed a cheaper way to produce high-efficiency solar cells and used it to make affordable, portable, flexible solar panels. Its solar cells now power troops' devices in the field, as well aircraft and satellites.



Plasma Improves 3D Electronics Printing

Space Foundry's plasma jet printer makes it easier to build electronics components on Earth and in space

A new approach to printing electronic components simplifies on-site manufacturing of electronics in space and on Earth.

With help from NASA funding and licensed technologies, San Jose, California-based Space Foundry has designed a plasma-based 3D printing process for electronics that has a number of advantages over other techniques. For one thing, it's a single-step approach that doesn't require heat or ultraviolet curing, as other methods do.

Eliminating the curing step, especially in space, “is huge logistically because you have to plan everything around astronaut up time,” said Ian Small, an electrical engineer at NASA's Marshall Space Flight Center in Huntsville, Alabama.

Post-print curing can also be a challenge on Earth, where, in addition to the added infrastructure needed for curing, some of the printed materials oxidize quickly in the atmosphere. Copper, for example, which is useful in electronics because it's highly conductive, is a challenge to cure and difficult to print on temperature-sensitive platforms.

Space Foundry has developed the hardware, software, and process for printing copper and other electronic materials without curing. The copper solution, as with any print material – or “ink” – introduced to the Space Foundry printing process, is aerosolized and then split apart by the plasma to create positive and negative ions, radicals, and electrons that react with the plasma. Print materials may undergo oxidation or reduction, depending on what electronic properties need adjusting for a particular material; the makeup of the plasma controls the adjustments.

“The uniqueness of their process, going through that plasma, lets them leverage some fancy chemistry,” said Small, who works on the NASA side of Space Foundry research backed by Small Business Innovation Research (SBIR) funding.

NASA's Ames Research Center in Silicon Valley, California, has awarded the company four SBIR contracts to test its plasma jet printing technology, including in a microgravity environment, though much of the work is being overseen by Marshall.

Space Foundry cofounder Ram Prasad Gandhiraman led the team that originally developed the plasma technology at Ames, where he was a contractor in the plasma processing lab, working on recycling of spent electronics in space. The company has licensed a plasma jet printing patent from Ames and another three from the Universities Space Research Association, which was his direct employer when he worked at NASA.

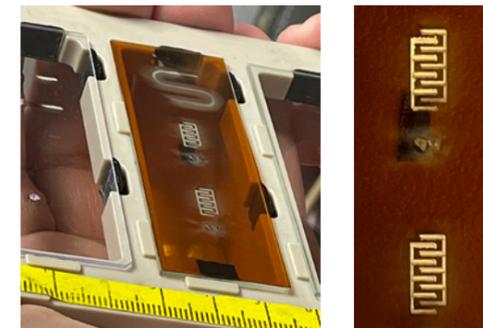
On Earth, Gandhiraman said the company is in talks with several aerospace and defense companies looking to use the process for a range of electronic component manufacturing, such as printing electronics on aircraft panels and wings. The plasma print process can also be used to print antennas for wearable sensors, mobile communications, and automobiles.

The company's current customers are primarily using the printer for research, including Boise State University; the Idaho National Laboratory; the University of Auckland, New Zealand; and Sandia National Laboratory.

Gandhiraman said NASA's backing of this plasma printing technology, from proof of concept through to funding for testing in the microgravity environment of a parabolic flight, have been critical to Space Foundry's success so far. “Without NASA support, we would not have come this far,” he said. ●

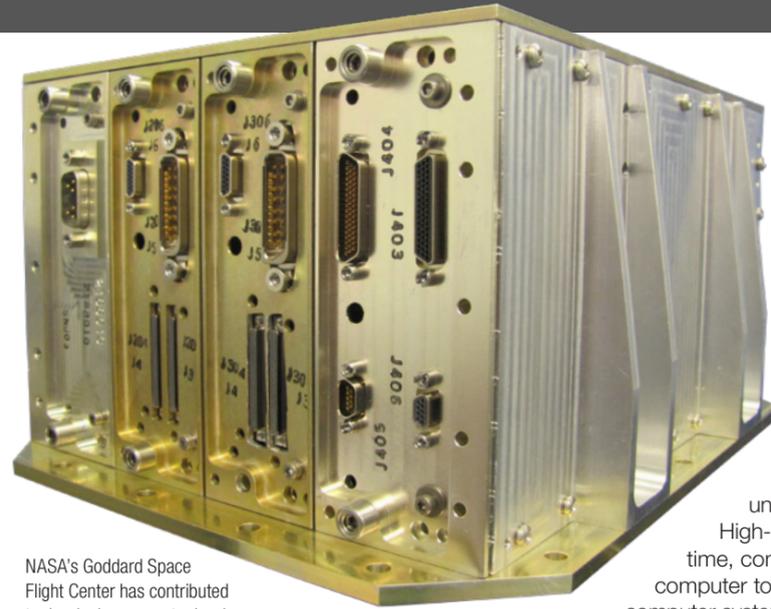


Space Foundry's Ram Prasad Gandhiraman, Dennis Nordlund, and senior engineers Pranay Doshi and Daniel Gutierrez testing the company's plasma 3D printing technology on a NASA-funded parabolic flight. Such flights create microgravity conditions without going to space. *Credit: Space Foundry*



Electrodes that can be used in biological and chemical sensors were printed in the microgravity environment of a zero-G parabolic flight. NASA has been a key supporter of the technology developed by Space Foundry to print electronics with a process involving plasma. *Credit: Space Foundry*

Computers Tough Enough for Space



NASA collaboration with industry and academia resulted in a reliable computer for CubeSats

A tough computer might sound like one that can be dropped from a high table, but in space, computers need to be tough both inside and out. The Center for Space, High-Performance, and Resilient Computing (SHREC) is a collaborative effort between government agencies, private industry, and academia to build out the capabilities of computers for specialized tasks – from large supercomputer clusters on Earth to small satellite systems in space. One tough computing project from this center, operated by the National Science Foundation (NSF), was produced under an agreement with NASA's Goddard Space Flight Center in Greenbelt, Maryland, and is now being used to make space more accessible.

CubeSats – small, modular, standardized satellites – have become a relatively cheap and easy way to send an experiment to space and are used by several universities to conduct tests in low-Earth orbit. At the University of Florida Center for High-Performance Reconfigurable Computing (CHREC), as SHREC was known at the time, computer science professor Alan George led a team to develop a small, all-in-one computer to act as an easy start to any CubeSat project. By building on existing embedded computer systems and adding radiation mitigation technology, the team constructed the CubeSat Space Processor (CSP) in 2015.

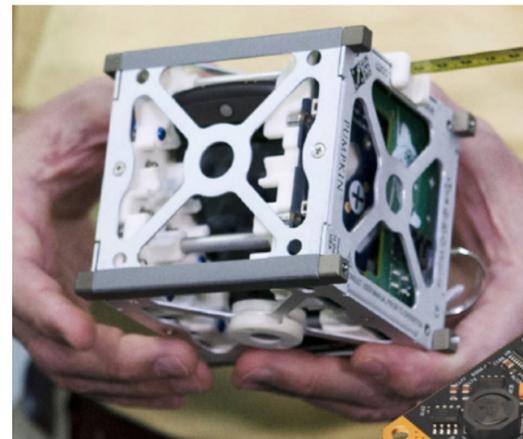
A good way to think about the insides of the processor is to compare them to the electronics inside a cellphone. Everything the computer needs is on one chip. A standardized dual-core CPU forms the brains of the processor, capable of running a Linux operating system or machine-level code. This makes it easy to write programs for the processor while still maintaining the survivability to endure long periods of time in the extremes of space.

The SpaceCube program, run out of Goddard, had advanced CubeSat processors in general, multiplying their computing power while keeping them small and inexpensive. As a partner agency in the NSF program, NASA technologists shared their knowledge, resources, and research of small satellites with CHREC as it developed the CSP.

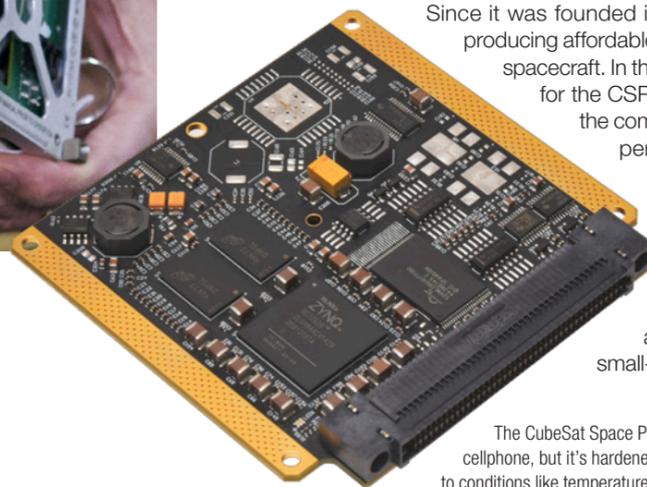
Since it was founded in 2002, Space Micro of San Diego has worked on producing affordable, radiation-hardened, and cost-effective electronics for spacecraft. In the 2010s, the company obtained a non-exclusive license for the CSP from CHREC. Over six generations of development, the company has managed to refine the design to attain higher performance with lower power. Because it's built with off-the-shelf hardware and in production volumes, the costs to produce Space Micro's latest CSP, released in 2017, are much lower than previous incarnations, and they're reliable enough that they can last many years in orbit. These are benefiting universities and other research institutions looking to conduct science and test technology in orbit, as well as high-reliability small-satellite programs in industry. ●

The CubeSat Space Processor has similar internal hardware to a modern cellphone, but it's hardened against the harsh environment of space and resistant to conditions like temperature extremes and radiation. *Credit: Space Micro*

NASA's Goddard Space Flight Center has contributed to developing computer hardware for spacecraft, such as the SpaceCube (pictured). Goddard personnel assisted the National Science Foundation's Center for High-Performance Reconfigurable Computing with building the first iteration of the CubeSat Space Processor. *Credit: NASA*



CubeSats are tiny satellites designed to be cheap and accessible platforms for experiments and are one of the easiest ways organizations can launch payloads into space. *Credit: NASA*



Software Keeps Cloud Traffic Moving



Credit: Getty Images

Process scheduler software originally developed for NASA helps ensure optimal use of cloud computing resources

From your streaming TV queue to the cloud storage where you keep photos, servers now play an important role in our lives. As the world continues to need more from these specialized systems, the jobs we task them with have to be scheduled to prevent bottlenecks. A system originally developed for this purpose at NASA is now available everywhere in enterprise computing.

The problem arose in the 1990s, when engineers and researchers needing to run their programs on the powerful shared systems at NASA's Ames Research Center in Silicon Valley, California, began to experience traffic jams. There was only so much space available in the memory and processors of their number-crunching machines, and overtaxing the system would lead to longer wait times for everyone.

The programmers, led by on-site software development contractor MRJ Technology Solutions (later acquired by Veridian), decided the best way was to make the computer equivalent of a crossing guard.

The Portable Batch System (PBS), first built in 1991, acts like a series of stoplights for supercomputers. Some computer tasks move forward, while others wait their turn. Tasks that take more resources are scheduled to run by themselves, while smaller tasks can run concurrently, keeping bottlenecks out of the system.

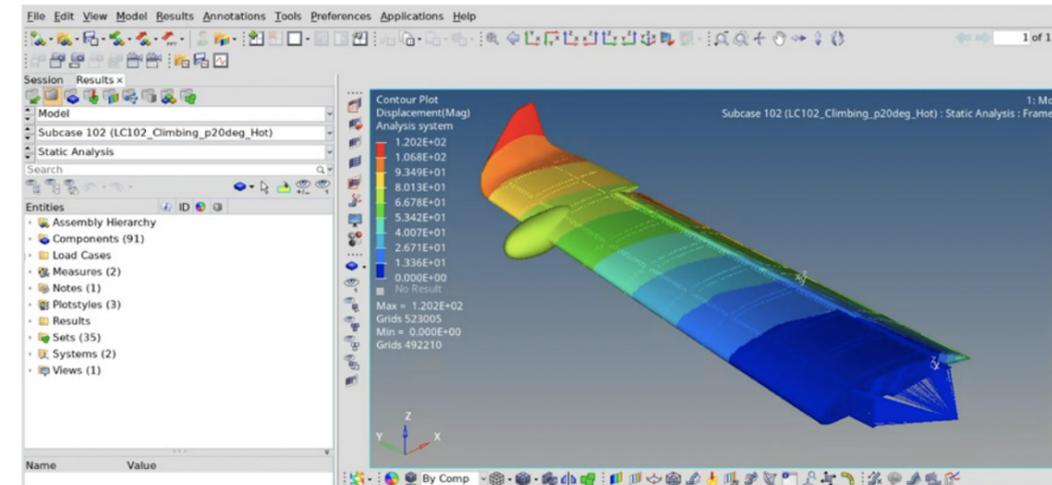
In 1998, after MRJ finished the original software for NASA, the Ames Commercial Technology Office, which would later become the Technology Transfer Office, gave the company authorization to distribute and support the software commercially. They split the system into multiple releases, including an open source version and an actively developed version called PBS Pro, with several of the NASA project developers remaining on the team.

"The original version didn't even have a graphical user interface," said Bill Nitzberg, who led PBS development at Veridian. "We built that on top as part of PBS Pro."

In 2003, Altair Engineering of Troy, Michigan, acquired active PBS development from Veridian. Since the early 2000s, the use cases of batch computing have continued to grow. In turn, PBS grew from a single piece of software into an entire suite, called PBS Works. Each tool in the suite performs a different function but still manages jobs in the queue. Hundreds of organizations use PBS Works, from large manufacturing firms like Ford and 3M, to scientific organizations like the Argonne National Laboratory.

With the advent of distributed computing providers like Amazon Web Services or Microsoft Azure, scheduling software has become a necessity, said Nitzberg, now the chief technology officer for PBS Works at Altair.

"Cloud services didn't exist when we first developed PBS, and now everyone uses them," he said. "People expect this software to be there now." ●



Screenshot from Altair Access, a newer part of Altair's solution set for high-performance computing, which makes it easy for end users to manage resources and workloads through PBS Pro. *Credit: Altair*

Antennas Find Their Cool



An ultra-thin, flexible heat shield insulation finds diverse uses in the commercial sector

A smartphone can have up to 13 internal antennas to send and receive signals for everything from the basic cellular connection to Bluetooth, WiFi, GPS, and more. With moisture and ultraviolet sunlight threatening to damage them, developing miniature antennas gets complicated. But a unique insulating material NASA developed makes it easier.

Scientists at NASA's Glenn Research Center in Cleveland developed an ultra-thin flexible material for an experimental spacecraft heat shield. A Hypersonic Inflatable Aerodynamic Decelerator (HIAD) can be stored inside a spacecraft and unfurled and inflated before descending to a planetary surface. The aerogel insulation Glenn developed for these heat shields can withstand temperatures of 1,100 degrees Fahrenheit for over 90 seconds.

Aerogels are extremely lightweight, effective insulators made by removing the liquid from a gel. The first practical aerogel insulations, made with silica, were created for NASA in the 1990s and have found widespread applications. But the Glenn team, led by Mary Ann Meador, now retired, wanted something more durable and flexible for HIADs, so they developed aerogels from polyimides – ultra-tough, high-performance plastics.

In addition to their strength and heat resistance, these award-winning polyimide aerogels block ultraviolet light while allowing radio signals to pass through. All of these characteristics also make them attractive to private industry (*Spinoff* 2017, 2019).

Laminated film company FLEXcon was so impressed that it secured an exclusive license for itself and affiliate Blueshift Materials Inc., based in Spencer, Massachusetts, to use the Glenn formula. The recipe to produce small quantities of aerogel in a lab couldn't effectively scale up for commercial manufacturing, explained Tim Burbey, Blueshift president. However, his team members used what they learned from the formula to develop their own polyimide aerogel, AeroZero, which became the company's first commercial product. It's a polymer aerogel about half as thick as a sheet of paper.

Blueshift also has an exclusive license from the space agency to use polyimide aerogels in communications antennas. The film provides a base onto which electronics are mounted to create a small antenna.

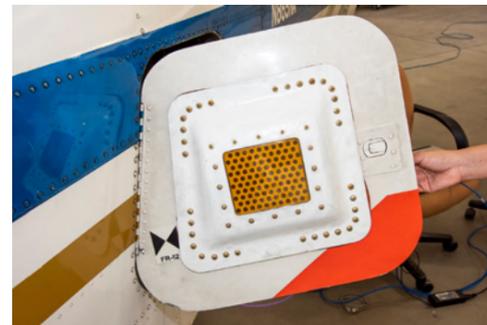
But the aerogel's properties make it ideal for other applications, too.

A race car team is using it to insulate vulnerable parts such as fuel tanks. The film can also be used as a laminate, so the team is using AeroZero inside the car's body to protect parts that can overheat.

Excess heat is also a challenge for some medical sensors used against human skin. Another Blueshift customer, Kernel, is using AeroZero to insulate its Flux sensor, which detects magnetic fields generated by brain activity. "The high thermal resistance improves both power consumption and external surface temperatures," said Burbey.

The porous nature of AeroZero – it's 85% air – makes it ideal for electronic applications. Air is a poor conductor of heat but allows radio waves to pass easily, so the material can insulate individual components while enabling faster transmission with lower signal loss.

It's also being used in computers, devices connected to the internet of things, and radomes – the protective housings that enclose antennas. But the greatest benefit for most users will be stronger, more reliable connections for mobile devices and longer-lasting batteries due to more efficient operation. ●



NASA designed a lightweight antenna using an aerogel that consisted primarily of air. The materials created flexible antennas with improved gain, bandwidth, and efficiency. The small, single unit combined 64 small antennas that outperformed the functionality of one large antenna, and it led to a new kind of aerogel created by Blueshift Materials, known as AeroZero. *Credit: NASA*



AeroZero, an ultra-thin polymer aerogel created by Blueshift Materials, laminates onto other surfaces such as the aluminum shown here. This process makes it possible to improve thermal management without adding weight or bulk. *Credit: Blueshift Materials Inc.*

Test Rockets Prepare for Distant Landings



Technology for spaceflight requires testing on Earth. Masten Space Systems built Xodiac to test terrain-relative navigation and hazard-avoidance systems for landings on Mars, the Moon, and more. *Credit: Masten*

Rocket-powered vehicles for testing lander navigation systems support space companies

How can a spacecraft land itself on alien terrain? NASA needed a better answer than "very carefully." To spur innovation towards the first autonomous landings on the Moon, the agency presented the Lunar Lander Challenge. In 2009, a young company called Masten Space Systems earned one of the top prizes.

The Mojave, California-based company used the prize money, as well as other NASA funding, to launch its rocket-powered vertical takeoff and landing service with Xombie, its first test vehicle.

"Xombie could fly at low altitudes and land repeatedly with great accuracy," said Colin Ake, Masten's vice president of lunar development. The rocket could also fly multiple times a day, allowing rapid collection of performance data.

So when NASA's Flight Opportunities program began at Armstrong Flight Research Center in 2011, Masten was one of the first seven flight providers. The program paid the company to fly landing navigation systems, both for NASA and for other companies.

Ongoing test flights are essential to prove systems work in real-life conditions – but flight test expenses alone can kill a promising technology. Funding from the program "helps companies bridge the gap between the lab and flight," said Ryan Dibley, Flight Opportunities campaign manager. The NASA funding was also essential revenue for Masten to continue to develop and build the next generation of vehicles to meet the demands of more sophisticated technologies.

The company's work would eventually come to help the Perseverance rover successfully land on Mars.

Early landing guidance systems for Perseverance flew on a helicopter, but that couldn't accurately simulate rocket-powered flight. Then Masten stepped in to provide a vehicle that would land like a spacecraft while collecting flight data.

In 2021, Perseverance successfully demonstrated that an automated navigation system can guide a targeted, rocket-powered descent. Now other aerospace companies are benefiting, because Masten also makes its services available directly to those who want to privately test their systems for landing on the Moon and beyond.

These services include extensive computer simulations, backed by data from more than 600 flights, before the vehicle ever leaves the ground. Next, the company conducts tether tests: abbreviated flights attached to a crane now using Xodiac, Masten's fifth generation of rocket-powered vehicles that can integrate and test systems from different companies. Finally, free-flight tests take place when there are no safety concerns. Ake explained that all of these steps are similar to services the company provides NASA's Flight Opportunities customers.

Thanks to a couple of Small Business Innovation Research contracts, Masten also offers plume field testing. The way soil and rock are blown around by the rocket as it descends to the landing site is the plume field, which can potentially damage navigation systems as well as the craft.

Masten is now working on a new test platform, Xogdor. The vehicle, in development with the help of funding from a NASA Tipping Point contract, will test technologies for NASA's next lunar missions, as well as those of private customers.

"Learning from things that NASA Flight Opportunities and other folks want to see and expect to see is enabling the next generation of landing rockets," said Ake. ●



This 1967 NASA Lunar Landing Research Vehicle, similar to the Lunar Module used during Apollo missions, was a flying machine that replicated descent to the lunar surface. New navigation systems will make landings safer. *Credit: NASA*

Swinging the HAMR



NASA technology and experience bring hybrid aircraft to the skies

From search-and-rescue operations to surveying farmland, remotely operated aircraft have become important to several industries. However, current multi-rotor designs have one drawback: endurance. Driving four or more rotors on a flying platform requires a lot of power. NASA research to develop a longer-lasting aerial system has paid off, with a former NASA engineer now using the design in commercial drones.

Since college, Bill Fredericks had worked off and on at NASA's Langley Research Center in Hampton, Virginia. During the early 2010s, he was an engineer at the center's Aerospace Systems Analysis Branch, where he worked on electric-propulsion projects including the experimental all-electric airplane X-57 Maxwell. Fredericks also tackled a challenge to build a remotely piloted vertical takeoff and landing aircraft (VTOL) that could fly for 24 hours. The Langley team designed and built Greased Lightning, a working half-scale model of this advanced aircraft, which made several flights in 2015.

While the prototype couldn't achieve the goal of 24 hours in flight because it was battery powered, the aircraft's technology showed promise. Fredericks decided he wanted to commercialize the technologies behind Greased Lightning. He founded the Advanced Aircraft Company (AAC) in 2016 in Hampton, Virginia, and licensed the patents behind the prototype. However, the NASA design only demonstrated the initial feasibility of a large hybrid VTOL aircraft, and the startup didn't have the funding to work on something of that size, so they started with something smaller.

The Hybrid Advanced Multi-Rotor aircraft uses a small combustion engine paired with batteries and electric motors to achieve flight times far greater than those powered by batteries alone. Bill Fredericks credits his work with NASA on the Greased Lightning project for enabling its development. *Credit: Advanced Aircraft Company*



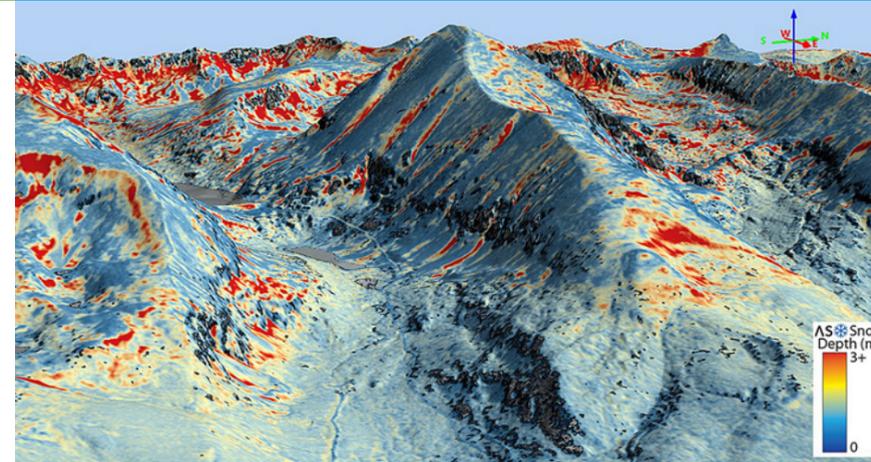
The company's new Hybrid Advanced Multi-Rotor (HAMR) aircraft is based on the hybrid electric propulsion system that would be required for Greased Lightning. Like a hybrid car, HAMR combines an internal combustion engine with electric motors. The aircraft runs on a gas engine about the size of a weed trimmer motor. That little engine drives a generator that supplies power to onboard batteries, which run the rotors. The result is a high-performance vehicle that can stay in the air for up to three hours, much longer than the roughly 30 minutes you get from batteries alone. This endurance means HAMR is useful for applications between typical multirotor drones and larger aircraft like helicopters.

"We span the gap between what manned aircraft perform today and what battery-powered drones perform today," Fredericks said.

HAMR's earliest customers are using it for applications like pilot training and surveying for methane leaks. AAC delivered its third aircraft in June 2021 and is looking to expand to markets such as civil engineering, infrastructure inspection, and municipal public safety. Fredericks said these early users are helping to put HAMR through its paces, and he hopes to continue improving the product to maximize the productivity of AAC's customers. ●

NASA efforts to build a large, gas-electric hybrid drone that could take off vertically and stay in the air all day led to this battery-powered prototype, called Greased Lightning, carried by engineers David North (left) and Bill Fredericks (right). *Credit: NASA Langley/David C. Bowman*

Getting Water Out of Snow with NASA Tech



Measuring snow depth and quality in the highest elevations of a mountain chain requires special sensors. NASA collected hyperspectral and lidar data from several mountain chains, using the technology to accurately measure snow depth and snow quality to calculate the amount of water contained in the snowpack. *Credit: NASA*

Sensors attached to an airplane measure snowpack in mountains to calculate the water it contains

How much water is there in mountain snowpack? That's a question science has been attempting to solve for decades. Finally, NASA-developed technology provides an accurate answer, using a cutting-edge airborne sensor system and sophisticated software that also predicts when snow will melt. For NASA, this deeper understanding of Earth's hydrologic cycle is another step toward helping future space missions measure frozen terrain elsewhere in the solar system, such as icy moons. Meanwhile, it's supporting flood prevention, drought mitigation, and sustainable farming on this planet.

Scientists have long known where to find snow, thanks in part to decades of NASA satellite imagery. But calculating how much water is contained in the snowpack is tricky. For communities downstream, it's like turning on a faucet and not knowing if you're going to get a trickle or a month's worth of water blasting out, explained Tom Painter, CEO of Airborne Snow Observatories Inc. (ASO).

Painter is the former lead scientist for the Airborne Snow Observatory mission at NASA's Jet Propulsion Laboratory in Southern California. There, he was instrumental in analyzing and modeling data from lidar and spectrometer sensors on an airplane to measure snow depth and melt rate. After successfully analyzing data for river basins in California, Colorado, and elsewhere, Painter cofounded a company that uses the one-of-a-kind system to measure snow around the world.

Formed in 2019 in Mammoth Lakes, California, ASO uses the technology developed at NASA to provide mountain snowpack data to farming organizations, municipalities, state agencies, hydroelectric utilities, researchers, universities, and consulting groups in addition to federal agencies, including the Bureau of Reclamation and the U.S. Geological Survey.

Around the world, mountain snowpack provides freshwater to over 1.5 billion people. With climate change making it hard to base snowmelt predictions on historical trends, accurate real-time measurements are necessary to plan and adapt, said Dan Berisford, who was flight coordinator for the original team at JPL. He now works part-time for ASO.

The JPL team started by creating a 3D map of each mountain before it snowed. These were generated with airborne lidar sensors, which work similarly to radar but use light instead of radio waves. Subsequent flights during the snow season also took lidar measurements. By comparing the two, scientists could measure snow depth.

ASO licensed the software developed for the NASA mission from the California Institute of Technology, which manages JPL. This enables the company to combine flight data with field measurements and other information such as weather conditions. The result is an accurate depiction of snow depth and snow-water equivalent.

Planning for wet and dry months throughout the year means preparing for the impact on hydroelectric systems and ensuring farmers can irrigate crops, while knowledge about heavy runoff can prevent devastating flooding.

Wes Monier, chief hydrologist for the Turlock Irrigation District in California and an ASO customer, said the data is "very instrumental" to decisions that affect residents, the ecosystem, and California's \$15 billion farm industry. ●



Both drought and flooding cause significant damage in a river basin, so it's important to know the volume of water that will reach a dam during snow melt. The Oroville Dam lake on the Feather River in the Sierra Nevada foothills experienced both extremes. Airborne Snow Observatories provides snowpack data to help municipalities, residents, and businesses prepare for winter runoff. *Credit: NOAA*

Stay Safe with Battery Testing for Space



Lithium-ion batteries are used in everything from mobile phones to power tools. Underwriters Laboratories makes testing standards for each of these. *Credit: Getty Images*



On the space shuttle Columbia flight STS-93, the first lithium-ion battery flown on a human spaceflight was used to power a video camera. While working at NASA's Johnson Space Center, Judy Jeevarajan devised the testing processes to ensure the battery was safe to use in space. *Credit: NASA*



NASA battery safety exams influence commercial product testing

Battery safety is incredibly important in space due to the risk of thermal runaway, a reaction where temperatures within the battery continuously escalate, potentially causing a fire or explosion. For two decades, Judy Jeevarajan was the woman in charge of testing them at NASA. Thanks to that experience, batteries for everything from industrial equipment to home appliances are tested using the methods she originally developed for orbit.

Jeevarajan began working at NASA's Johnson Space Center in Houston in the 1990s, developing advanced testing technologies and eventually becoming responsible for approving all batteries flown for human spaceflight. For a space shuttle flight in 1999, astronauts wanted to bring a digital video camcorder aboard. Previous video cameras on the shuttle used battery chemistries already authorized for space, but the era of lithium-ion cells was new territory for space missions.

To test these batteries, her team used a hydraulic press to probe their designs for tolerance to internal short circuits and devised a vibration test that would ensure the intense shaking at launch wouldn't lead to a catastrophic failure. Jeevarajan's tests provided data that confirmed the cells had a negligible chance of developing the internal shorts that would lead to thermal runaway. Once the design was proved safe, the camcorder's lithium-ion batteries were approved to go to space. Her work expanded to testing batteries for every consumer-grade device and payload brought into the International Space Station, ensuring they were at extremely low risk of starting a fire.

For more than 100 years, Underwriters Laboratories Inc. (UL) of Northbrook, Illinois, has developed standards and testing modes for all modern appliances and technologies, ensuring that everything from home electronics to industrial machinery is as safe as it can be. After Jeevarajan met engineers from UL at a meeting on battery safety, she became a member of the UL Standards Technical Panel for battery safety and helped verify the workings of a new battery-testing machine. Over the next decade, she used the experience she gained at NASA to work with UL to further develop and promote the adoption of new testing methods.

After the lithium-ion batteries powering the Boeing 787's avionics suffered from thermal issues, Jeevarajan assisted in investigations at NASA and created a new method to induce thermal runaway in a single lithium-ion cell by attaching a heater around it and seeing how fire would move through the system. Today, this technique is a common way for battery manufacturers to test battery cell designs before they are transported.

Jeevarajan joined UL's nonprofit arm full-time in 2015, bringing with her knowledge she'd gained at Johnson, including her techniques for inducing thermal runaway. These are now part of a UL-defined test method for testing cells in large lithium-ion battery systems, like those found in batteries for storing power on the electrical grid. ●

When the Boeing 787's lithium-ion batteries had thermal issues, NASA helped establish ways to ensure cells flown on airliners didn't face the same problems. Today, these methods developed at NASA are a common way for manufacturers to test battery designs before they are flown. *Credit: Getty Images*

Keeping Warmer in the Great Outdoors



Insulating with Air

The first aerogels were invented before NASA existed – but they were too fragile to use. That changed in the 1990s, when NASA's Kennedy Space Center in Florida was on the hunt for better insulation to store and transport cryogenic rocket fuel. Aspen Systems had an idea for incorporating that too-brittle aerogel into flexible insulating blankets. A decade and 10 NASA Small Business Innovation Research contracts later, the company spun off Aspen Aerogels to specialize in what became one of the most successful, widespread spinoffs in the space agency's history.

The NASA collaboration has since spawned another, with Latham, New York-based PrimaLoft, and the results are found in an array of products that can keep even the most intrepid outdoor enthusiasts, and their gear, warm.

What Is Aerogel?

Aerogels are made by removing all the moisture from a gel (in this case, generally silica) while leaving the solid structure intact. The resulting material is almost entirely air, pocketed in tiny chambers, and is nearly impervious to heat. Aspen soaks treated material in an aerogel precursor, then flash dries it to leave aerogel coating every fiber. PrimaLoft encapsulates the blankets to prevent dust.

Because encapsulated aerogel blankets are thin and form a thermal barrier even under high pressure, the material is ideal for smaller areas that get pressed against cold objects – specifically, the hands and feet. Seattle-based Outdoor Research uses encapsulated aerogel blankets in its signature footwear for mountain climbing, as well as in gloves, campsite footwear, and a beanie.

Credit: Getty Images

Cases

Even on a mountainside, technology – phones, smart watches, cameras – comes with us. But batteries don't do well in extreme temperatures. Inspired by a disappointing camera failure during a Rocky Mountain New Year's trek, Cold Case Gear of Pagosa Springs, Colorado, designed a line of aerogel-insulated pouches to protect tech.

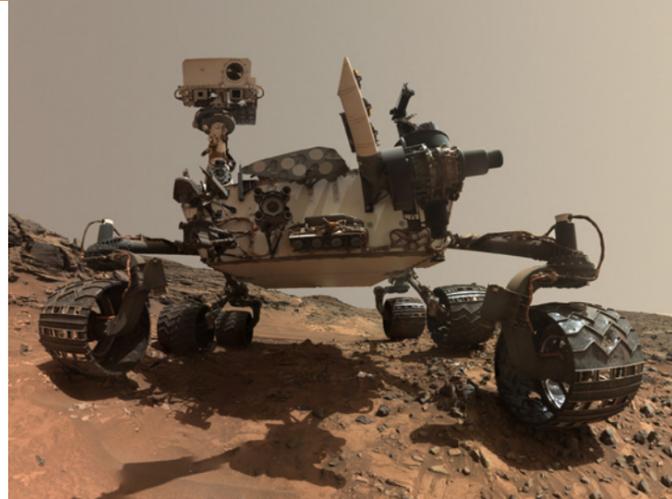
Outerwear

Based on Aspen's invention, PrimaLoft invented a more breathable aerogel insulation that infuses aerogel dust, processed into tiny, uniform particles, inside ultra-fine fibers. Today, this new twist on the NASA-pioneered aerogel blankets is in jackets, snow pants, and sleeping bags made by SITKA Gear, headquartered in Bozeman, Montana, now a subsidiary of W.L. Gore & Associates.

Footwear

These aerogel materials perform as well as traditional insulation when dry – and better when wet – at half the thickness and far less weight.

The 'Cobot' Revolution Is Coming



While NASA's Curiosity rover represented the cutting edge of the space agency's robotics when it arrived on Mars in 2012, it has to spend about three hours heating up lubricants for its gears each time it sets out across the planet's surface. To help future rovers save time and energy, NASA has invested in bulk metallic glass for gears that require no lubrication. *Credit: NASA*



Flexsplines represent a potentially major industrial application for bulk metallic glass. The thin, flexible, cup-shaped gears are integral to the strain wave gears common in robotics. They're typically cut, ground, and drilled from steel billets in a process that is long and costly. The flexspline shown on the right, however, was injection molded from metallic glass in a cheaper, simpler process. *Credit: NASA*



Smaller, smarter, and better controlled than their industrial counterparts, collaborative robots – or "cobots" – are designed to safely interact with humans and perform a wide range of tasks. While they are becoming a fast-growing sector of the robotics industry, their cost, largely driven by expensive precision gears, is a major obstacle to widespread adoption. Amorphology plans to significantly reduce that cost by injection molding gears from NASA's bulk metallic glass. *Credit: Getty Images*

Bulk metallic glass could slash prices of collaborative robots and lead to advanced 3D-printed metals

While cartoons have long imagined robot butlers, so far most of us have only ever gotten a hands-free robot vacuum.

This is due to cost and safety, according to Glenn Garrett, chief technology officer at Amorphology Inc. Most automated machinery is still only affordable to large manufacturers. And while robots can improve efficiency, they are strong and largely oblivious to their surroundings – posing a safety risk for human colleagues.

That's where "cobots" come in: collaborative robots are smaller, smarter, and more responsive, with tighter self-control. Thanks to leaps in artificial intelligence and sensors, these "friendlier" robots exist. But they're too expensive for many companies that could benefit from them.

Getting the cost down, explained Garrett, could come down to cheaper gears, which can drive at least half the cost of robotic arms.

Pasadena, California-based Amorphology hopes to drop the price of cobots with advances originally made for NASA's planetary rovers.

Most gears are made of steel, which is both strong and wear resistant. But steel gears need liquid lubrication, and oils don't work well in frigid environments like the lunar or Martian surface. So NASA's Curiosity rover, for example, spends about three hours warming up lubricants every time it prepares to start rolling.

With an eye toward solving this and other materials-related issues, in 2010, NASA's Jet Propulsion Laboratory in Southern California hired Doug Hofmann, now the principal scientist of the center's Materials Development and Manufacturing Group.

Hofmann was familiar with an emerging class of specially engineered materials called bulk metallic glass, also known as amorphous metals. These are metal alloys that can be cooled from liquid to solid so quickly that the atoms remain randomly arranged – like those in glass – giving the materials properties of both glass and metal.

Depending on the metals used, the resulting material can make for long-lasting gears that don't need lubrication, Hofmann explained.

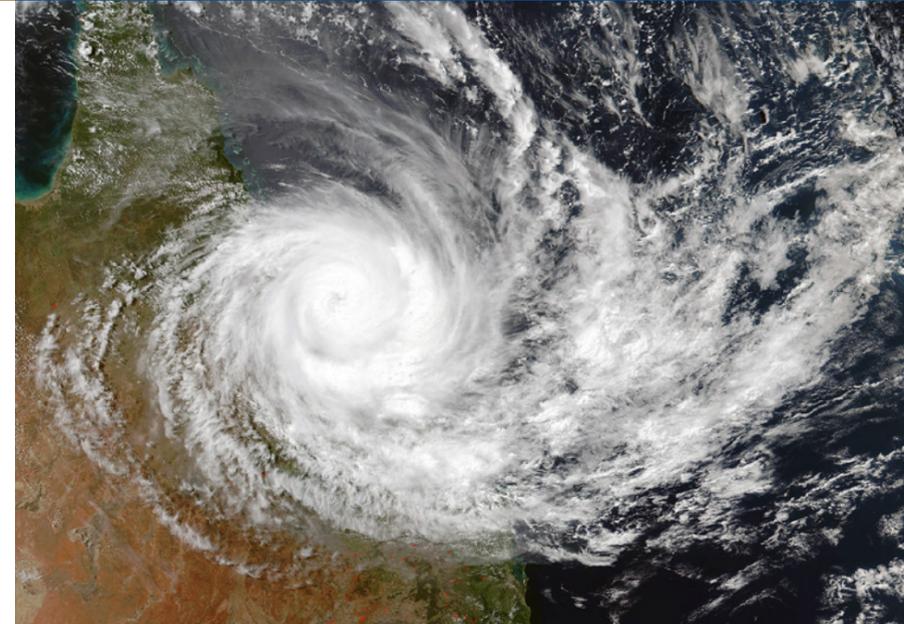
Amorphous metals are also "designed to have low melting temperatures, because to make a metallic glass, you have to cool the alloy faster than it can crystallize," Hofmann said. This low melting point makes bulk metallic glasses easy to use in injection molding, a far cheaper manufacturing process than cutting and grinding from steel.

One of the most common gear components in robotic arms is the flexspline, the centerpiece of a strain wave gear assembly. "It's a very strange-looking gear if you've never seen it, but it's the heart and soul of a precision robot," said Hofmann, who cofounded Amorphology in 2014.

A flexspline, which is thin and intricate, can be molded from amorphous metals for about half the cost of machining it from steel, he said.

Through the California Institute of Technology, which manages JPL, the company licensed several patents for technology Hoffman had developed for NASA. And today its largest customer is one of the world's foremost manufacturers of strain wave gears. ●

Satellite Software Helps Global Forecasting



With more efficient data transmission at polar downlinks, the National Oceanic and Atmospheric Administration (NOAA) can offer use of its antennas to other organizations, helping people around the globe stay informed of potentially dangerous weather. *Credit: NASA*



The Joint Polar Satellite System constellation will consist of satellites on polar orbits. By using satellite scheduling software, NOAA is able to ensure that its weather and scientific satellites can get data to meteorologists quickly and efficiently. *Credit: NASA*

Satellite scheduling software helps to consolidate data acquisition and improve weather forecasting

Weather satellites gather data throughout their orbits but can only send that information to Earth as they pass over a ground station. To help coordinate those transmissions, NASA engineers-turned-entrepreneurs created satellite scheduling software that will help National Oceanic and Atmospheric Administration (NOAA) observations get to Earth as quickly as possible, letting forecasters make better predictions that could save lives.

In the 1990s, Ella Herz was a contractor for Rockwell at NASA's Johnson Space Center in Houston, where she developed software for space shuttle mission control, and her husband Alex worked on ground control systems at NASA's Goddard Space Flight Center in Greenbelt, Maryland. His primary project was control software for spacecraft designed to do things like map forest health. There he met Doug George, a fellow programmer who was instrumental in these efforts.

The team saw room for improvement in the tools used to time events in orbit. In 2000, the three former NASA experts started Greenbelt, Maryland-based Orbit Logic to turn their work into commercial software for the growing number of satellites in orbit.

One result was STK Scheduler, built on their experience with space mission scheduling and ground support software. In conjunction with Systems Tool Kit (STK), an existing commercial program that several satellite operators use, modern versions of STK Scheduler can run on everything from desktop computers to cloud systems and web servers. This versatility caught the interest of NOAA, which needed a new system to manage its observations.

While most big-picture weather-observation snapshots over wide areas of land are made from equatorial geostationary orbit, closeups of Earth are generally made from polar orbits. With the only locations repeated on every orbit being the North and South poles, observations are generally downlinked within these regions. As a result, it is important that scheduling software is used to ensure downlinks are coordinated at the right times to get the most out of these satellites.

Since the 1970s, NOAA has worked alongside NASA to design, build, and launch satellites. For each one, NOAA utilized whichever scheduling system was delivered at that time, which led to several, often incompatible solutions.

Adopted in 2021, the Enterprise Automated Scheduling Implementation (EASI) software is NOAA's solution to this problem, and STK Scheduler powers the whole thing. NOAA can schedule each satellite with knowledge of what the others are doing and get data down more efficiently. In addition to helping NOAA get more data, EASI allows the agency to offer leftover bandwidth to partners in need, such as meteorologists with the European Organization for the Exploitation of Meteorological Satellites and others, helping people around the world get a better grasp on the weather within their regions. ●

From a Lightbox to Lamps



The Ario Lamp, based on NASA-funded research into circadian rhythms, changes color throughout the day to help alleviate jet lag, promote better sleep, and improve wakefulness. *Credit: Ario*

Wireless LED lamps keep people's circadian rhythm in check

Dale Dell'Ario had a glowing box in his living room, and he wanted to share it. Dell'Ario had retired in 2013 from a long career in medical device manufacturing, where he'd developed lighting for phototherapy treatments. These high-intensity blue lights are used to treat ailments such as infant jaundice and other skin conditions. Because he was familiar with the science and engineering behind light therapies, he wanted to do something that would help in ways beyond medicine.

For two decades, the National Space Biomedical Research Institute (NSBRI) looked at the ways long-duration spaceflight affected astronauts, funded with grants from NASA's Johnson Space Center in Houston. NSBRI research from Harvard Medical School's Steven Lockley found that when photoreceptors in the eye sensed blue light, the brain suppressed production of melatonin, the chemical in the brain that manages sleep.

Dell'Ario had read Lockley's research and attended a lecture with his team. Armed with this new knowledge, he decided to use his experience creating light fixtures to make something that could help people reset like astronauts, who battle multiple sunrises and sunsets that can cause havoc on the internal body clock.

"I wanted to design a lamp that provided blue light in the morning and removed it in the evening," Dell'Ario said.

He constructed a prototype using LEDs with adjustable colors in a wooden box, which sat on his coffee table until he showed it to his neighbor, who made frequent plane trips for work. Because the neighbor, Brian Hoskins, always returned tired from traveling and crossing multiple time zones that confused his body clock, Dell'Ario let him borrow the prototype, and he was immediately smitten.

"I tried the light and it immediately made me sleep better," Hoskins said. "This light really helped to reset me."

The pair founded Seattle-based Ario in 2015, with Hoskins helping incorporate an internet connection to the light to enable automatic, time-based color adjustments. The final version is an adjustable floor or table lamp with WiFi connectivity and a motion sensor.

The Ario Lamp's creators say it can be found in thousands of homes. While the lamp is primarily aimed at individuals looking to manage their circadian rhythms, it has also found success in the hospitality industry. Stanford University also installed the Ario Lamp in its housing for business school students and on-campus hotel for visiting executives who need to recover from jet lag. ●



On the space station, these tiny cabins are where astronauts get shut-eye. Working under artificial light and experiencing more than a dozen sunrises and sunsets each day could disrupt astronauts' body clocks, and for decades NASA funded research into mitigating this. *Credit: NASA*

'Positive Energy' Captures Contaminants



The Carafe Pitchers have been the most popular Aquaspace product since Western Water International's early days, due to their combination of effectiveness and affordability. *Credit: Western Water International*

Aquaspace filters still build on research for Apollo, space shuttle water purification

The carbon-based compound in Aquaspace water filters started out more than 35 years ago in Mike Pedersen's basement, with a stack of NASA research. Now the filters have appeared in the White House, Environmental Protection Agency (EPA) facilities, and every drinking fountain in the D.C. Public Schools system, in addition to homes across the country.

In the 1980s, Pedersen decided to start a business in water purification, and he learned that the space agency was a step ahead of the industry. NASA has been working on water purification since its beginning, as drinking water supply is extremely limited in spacecraft.

Pedersen contacted NASA requesting information and received reports on work NASA's Johnson Space Center in Houston had funded before the Apollo and space shuttle missions, developing water purification systems that used positively charged silver ions to attract and destroy pathogens. The reports consistently showed that stronger positive charges better captured contaminants, he said, noting that this was not an approach others were taking at the time.

Pedersen applied the same principle to different filter media and contaminants more relevant to household drinking water. "They did studies to do one thing, and I saw you could do other things," he said. "If it wasn't for the NASA research, I never would have gotten there."

Instead of using silver ions to capture microbes, he worked on increasing the positive charge of activated carbon to remove contaminants like organic chemicals, toxins, chlorine, and lead. He founded Western Water International of Forestville, Maryland, using the brand name Aquaspace.

The company developed activated carbons that not only had high electropositive charges but also excelled at trapping specific impurities. The Aquaspace compound is a composite of several of the resulting carbons.

By the mid-1990s, the company offered a variety of countertop, under-sink, portable, and whole-house filters (*Spinoff* 1988, 1993).

Aquaspace filters effectively end up costing less than other alternatives because they last a full year, Pedersen said, and they also capture a larger range of contaminants due to the modified charges of the activated carbon.

What began as a basement operation now occupies a 6,000-square-foot facility with five employees, Pedersen said, noting that the company grew mainly through word of mouth, although Apollo astronaut James Lovell was also the company spokesperson for 17 years.

It also helped that for 12 years, in the 1980s and '90s, Aquaspace filters were used in the White House. And more recently the EPA selected Aquaspace filters for the childcare center at its D.C. headquarters.

In 2017, Washington, D.C. schools decided to shoot for lead levels of just one part per billion, well below regulations. Several companies were invited to meet the challenge, but only Aquaspace filters succeeded. They're now in all water fountains and kitchenettes in the city's public schools.

One thing that hasn't changed since the company's start is that its Carafe Pitchers remain its top seller. "Nowhere else can you get that quality for that price," said Pedersen. "I call it the No. 2 pencil of water filtration, because it's just not going away." ●



Aquaspace water filters' popularity has been bolstered by several high-profile customers over the years. In 2017, they proved to be the only filters that could hit D.C. Public Schools' target for lead elimination, leading to their adoption in all of the school system's fountains and kitchenettes. *Credit: Getty Images*

From Spacesuits to Racing Suits

NASA-funded materials give race car drivers more comfort and better performance

From space shuttle tire engineering ending up in road tires to zero-gravity body posture studies helping make comfy car seats, decades of space development have resulted in better cars. Now a technology originally designed for spacesuits is being used to make temperature-regulating underwear for the people who drive the fastest vehicles on land.

For spacewalks to even be possible, spacesuits need major insulation and temperature controls. In the 1980s, NASA's Johnson Space Center in Houston entered into a Small Business Innovation Research (SBIR) contract with the Triangle Research and Development Corporation to develop a glove material that would maintain a steady temperature. The secret was phase-change materials, which absorb and release heat through basic characteristics of matter. As the material melts or solidifies, the temperature stays around the melting point, ensuring it always feels just right.

Triangle's work for NASA incorporated microcapsules containing a phase-change material into a prototype spacesuit glove insert. These inserts never made their way into orbit, but the technology showed promise. In the 1990s, a company now known as Outlast Technologies acquired exclusive patent rights from Triangle to build the microcapsules into insulation and fabric. Working with many partners, Outlast has incorporated its "Thermocules" into outdoor gear, bedding, and sportswear (*Spinoff* 1997, 2004, 2009, 2012, 2013, 2017, 2021). One partner brought Outlast to a different kind of sport altogether: motorsports.

Speed is a bigger priority in race cars than comfort, so they don't have amenities like air conditioning. Sitting in her boiling car before a race, amateur racer Fiona James believed the key to making racing more comfortable might be in the full-body undergarments worn by drivers. James founded Cambridge, England-based Walero in 2014, and her search into temperature-regulating materials brought her to Outlast.

Outlast has been used in underwear before, but race undergarments have some distinct differences. In a race car, there's always the risk that a crash or mechanical trouble could cause a fire. Bonding Outlast to a layer of a fire-retardant material made it able conform to the regulations set by sanctioning bodies of international motorsports. In product testing, a driver wearing phase-change materials had a lower core temperature and heart rate and made fewer mistakes behind the wheel, resulting in a faster, more consistent lap time.

James said Walero's products have been adopted by drivers across all levels of racing since hitting the market in 2015. Walero's American distributor, HMS Motorsport in Mooresville, North Carolina, has sold its garments to both amateur racers and professional NASCAR drivers. The company plans to launch other Outlast-based products soon, but its primary market is still racers looking to get an edge against the competition. ●



Due to extreme temperatures in the cockpit, drivers in almost every major racing championship wear Walero for its cooling properties. Cristiana Oprea (pictured) wears it while driving for the European Rally Championship. *Credit: Walero*

While astronaut Drew Feustel (left) isn't wearing a spacesuit behind the wheel of this NASCAR racing vehicle, developments in spacesuit technology have seen adoption in auto racing. In the 2021 NASCAR season, several drivers are wearing undergarments made by Walero that utilize phase-change materials originally designed for NASA under an SBIR. *Credit: NASA*



Spacesuit gloves (left) have to be both dexterous enough to use tools and insulating enough to protect against the temperature extremes of working in space (above). Collaborating with industry, NASA explored the use of phase-change materials for these purposes, which was later commercialized under the name Outlast. *Credits: NASA*

Some Engineering Is Only Skin Deep

Ability to finish surfaces of 3D-printed superalloys improves performance for engines, industry

Recent advances in 3D printing with metals are making it an increasingly attractive option, often offering both cost savings and higher-performing components. The resulting parts, however, have one major drawback that threatens to offset the advantages of metal 3D printing, or additive manufacturing: they have much rougher surfaces than those produced by traditional methods. This can dramatically reduce performance and durability in many applications.

Smoothing these surfaces, especially on strong, high-performance metals, is its own challenge, and it's one NASA has undertaken in hopes of both improving rocket engines and making 3D printing viable across more industries.

Paul Gradl has led several additive manufacturing projects at NASA's Marshall Space Flight Center in Huntsville, Alabama, including efforts to use the technology to build rocket engines. "Additive manufacturing allows us to fabricate parts much quicker, and we see cost savings because of that," he said, adding that 3D printing could reduce engine weight and allow for part reduction, eliminating joints.

Components like combustion chambers, injectors, and nozzles traditionally required multiple parts to be manufactured and then joined or fastened together. Instead, they can be printed as entire units, reducing the number parts and, therefore, the number of seams that can become points of failure. But rough surfaces threaten to reduce fatigue life, speed up corrosion, and cause turbulence in fluid flows, said Gradl.

So he contacted REM Surface Engineering of Southington, Connecticut. Founded by CEO Justin Michaud's grandfather as a decorative plating supply company in the 1960s, REM had since developed a combination of chemical and chemical-mechanical techniques for metal surface finishing.

The company had already successfully finished surfaces of 3D-printed metal parts but did not have viable processes for some metals NASA was interested in, including certain "superalloys." Under two Small Business Innovation Research (SBIR) contracts from Marshall in 2018 and '19, REM developed the ability to surface-finish parts printed from Inconel 625 and 718, popular nickel-based superalloys of interest to the agency and industry. The funding also helped the company develop surface finishing for JBK-75, an iron-nickel-based alloy, and NASA HR-1, a derivative of JBK-75 that's resistant to the high-pressure environment of hydrogen engines.

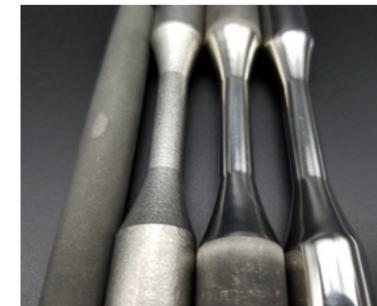
Gradl said starting with Inconel would both meet NASA's immediate needs and provide a commercial market for the company's work. The ability to process JBK-75 and NASA HR-1, meanwhile, would help the agency advance its Rapid Analysis and Manufacturing Propulsion Technology project, which aims to improve rocket thrust chambers while bringing down their cost, in part through 3D printing with composite materials.

REM's work with superalloys has drawn interest from commercial space companies, the auto racing industry, and producers of turbomachinery such as gas turbines and jet engines. Additional possible markets include radio frequency waveguides and even a potential nuclear fusion reactor, Michaud said.

He noted that the work is also helping NASA quantify the performance of various 3D printing materials, components, and techniques, which will help other companies enter the business. "NASA is taking away the barriers to entry and opening up space for more success across the industry," Michaud said. ●



In this hot fire test at Marshall Space Flight Center, a nozzle printed from a NASA-developed superalloy metal is used inside the combustion chamber. The nozzle's surface was polished by Southington, Connecticut-based REM Surface Engineering, with a process and tools developed under SBIR funding from Marshall. *Credit: NASA*



Building rocket parts using 3D printing is less expensive than traditional manufacturing methods and can facilitate complex shapes without joints. But the technique leaves rough surfaces (left) that could cause turbulence, corrosion, and accelerated wear if not perfectly polished (right). *Credit: NASA*

REM Surface Engineering already had experience finishing 3D-printed surfaces but had never worked with certain high-performance superalloys NASA needed for rocket engines. With the help of two SBIR contracts, the company designed and constructed this large-scale chemical polishing cell, where it polished NASA's superalloy nozzles. Today the company is ready to use the equipment for commercial clients. *Credit: REM Surface Engineering*



NASA's X-59 Quiet Supersonic Technology aircraft requires the use of creative and strategic supersonic technologies to control and soften the jarring sound as the aircraft passes the speed of sound, known as a sonic boom.

SPINOFF Features

How will we feed the world's burgeoning population of billions amid a changing climate, increased urbanization, and other challenges? As manufacturing gets smarter, can we help make it safer? How can we keep the lights on – and the phone batteries charged – globally, without depleting Earth's resources beyond return? The answers to these important questions may just come from space. Turn the page to learn more.

A Moveable Feast: Plant Research for Space Advances Earth Agriculture

NASA's vertical farm, the first in the country, provided a foundation for expanding the controlled environment agriculture industry



The United Nations predicts Earth will have to feed another 2.3 billion people by the year 2050, with most concentrated in urban centers far from farmland. Current agriculture may not have the capacity to feed that many people, and it threatens future production by depleting soil of essential nutrients and contaminating freshwater supplies and soil with pesticides and herbicides.

Conventional farmers are working to make their fields more efficient and productive and less harmful to the environment – at times with innovations and other support from NASA – but these changes are only part of a long-term solution.

NASA has been working for decades to tackle similar problems for space exploration. Reusing a limited water supply, minimizing energy consumption, and eliminating soil as a growth medium are just a few ways the agency stretches the limited resources available in space. Research into solving these challenges to grow plants in a closed environment like a spacecraft inspired NASA to build the first vertical farm in the United States, creating a foundation for the controlled environment agriculture industry to build on. The lessons learned are inspiring an unconventional new generation of farmers.

These practices could help feed Earth's burgeoning future generations, said Nate Storey, chief science officer at Plenty Unlimited Inc., one of several companies building on NASA plant-growth research with an eye toward bringing agriculture into the urban environment.

Plenty's farming model uses less than 1% of the water required by traditional farming and yields a consistent harvest year-round, regardless of weather. Built inside cities, this growing environment is also completely contained,

One way Plenty Unlimited maintains plant health is by using robotics in nearly every step of the farming process. Proprietary technology grows the company's Spicy Mizuna Mix, shown here, and relies on data to optimize growing conditions. The growing environment mimics the closed-loop environment developed by NASA in the Biomass Production Chamber that demonstrated how to grow plants without sunlight or open air. *Credit: Plenty Unlimited Inc.*

Plenty Unlimited Inc. of San Francisco relied on data published by NASA about the first controlled environment vertical farm in the United States to design and build a highly automated urban farm that uses 1% of the water traditional agriculture requires.

eliminating the threat of drought or pest invasion. Indoor and vertical, these farms grow more crops in a much smaller area. The two-acre Plenty farm produces approximately the same yields as a 720-acre outdoor farm.

Called controlled environment agriculture or CEA, this combination of plant science and environmental control techniques optimizes plant growth inside an enclosed space. Unlike a traditional greenhouse, this new vertical approach to cultivation leverages technology and data to maintain ideal growing conditions in a completely closed structure. These tools make it possible to filter contaminants from water for crops (keeping them out of food) and deliver the exact nutrient balance to feed any crop throughout its life cycle. Artificial lighting can eliminate the effects of fluctuating solar light, nurturing growth with a precise mix of beneficial red, blue, and green light at the right intensity and duration. Environmental controls also maintain proper temperature and humidity to prevent disease.

The approach produces fresher, healthier, more flavorful plants.

After decades of NASA research, the CEA industry expanded dramatically in the 1990s due in part to hundreds of millions of dollars invested by high-tech companies. Currently some estimates value the global market worth about \$2.9 billion, the vertical farming market is projected to reach \$7.3 billion by 2025.

"The entire industry is built on NASA research," said Storey, noting that NASA publications and NASA-funded studies by universities proved that controlled environment farming was possible and laid the foundation for a viable commercial industry.



The interior of the Biomass Production Chamber at Kennedy Space Center in Florida replicated the closed growing environment astronauts will use in space or on other planets to grow fresh crops. The chamber helped NASA provide critical data for the indoor farming industry. *Credit: NASA*

"This was a closed-loop system," explained Wheeler. "The system recycled and reused as much as possible – water, air, nutrients – making it self-contained, just as it will have to be in space or on another planet."

Adjustable shelving created vertically stacked levels of hydroponic trays, with just enough water and nutrients flowing through them. Between each shelf, a bank of high-intensity discharge lamps simulated sunlight. Air circulated across the plant canopy and vented back through the lights, making it possible to remove excess heat, control the humidity, and help maintain and measure other environmental conditions.

Dozens of plant experiments were conducted during the chamber's nearly nonstop operation between 1988 and 2000, producing a "firehose of data." Wheeler said the team measured multiple data points, including biomass yields, CO₂ removal, O₂ production, and more. Growth recipes (optimal conditions for a plant species) and other data were made publicly available in databases and hundreds of technical reports and peer-reviewed papers. NASA-funded university studies shared still more results.

From that body of work, Storey learned the techniques and benefits of a closed-loop system. He said Plenty adopted the "nutrient film technique" that NASA employed, growing plants without soil and with minimal water. This hydroponic system houses seedlings in shallow channels, circulating a constant film of water that contains all the nutrients the plants require. The roots form a thick mat in the channel, allowing them access to both the air and water they need.

But the San Francisco-based company houses this system in its own vertical infrastructure. Tall, dual-sided towers hang from the ceiling in rows with water flowing from top to bottom. The water is then collected and filtered, and its nutrients are replenished before it's recirculated. When the seedlings begin to grow, the result is a wall of greens – a large, vertical canopy.

"We learned that a large growing surface improved uniformity and plant performance – it was healthier for the plants and easier to maintain," said Storey. "Humidity and temperature management at the canopy is more uniform, which is important to support stress-free growth."

Space-Inspired Farming

From the start, NASA knew it needed to provide astronauts with food in addition to building their living environment. Combining the two requirements resulted in a bioregenerative life-support system. Plants would recycle waste into resources, produce breathable oxygen, and remove CO₂ from the air, all while providing fresh food to supplement prepared meals.

The earliest experiments used algae, but turning that plant material into palatable food was too complicated, recalled Ray Wheeler, plant physiologist at NASA's Kennedy Space Center in Florida. So the Closed Ecological Life Support System (CELSS) program began funding research with universities to identify the best plants for space and their ideal growth conditions.

Meanwhile, the agency built a prototype growth chamber to replicate and expand on the university findings. NASA needed to scale up those small experiments to confirm edible crops could adequately support an astronaut before depending on such a system, explained Wheeler.

"Growing plants or crops is a multi-functional life-support approach," he said. "But we needed to answer the question, can you do this in a closed environment like you have in space?"

As the lead for Advanced Life Support Research, Wheeler helped conduct research in the Biomass Production Chamber, built in the late 1980s inside a decommissioned hyperbaric chamber left over from testing the Mercury space capsule. The chamber interior was modified to create the country's first fully operational vertical farm.

By controlling every element of the environment, Plenty doesn't need to use harmful chemicals such as pesticides and herbicides. But the company is continually researching ways to improve crop conditions.

Plant-Growth R&D

Different plants require different balances of water, nutrients, light, airflow, and more. NASA studied and documented all this information for dozens of species, and now Green Sense Farm Holdings Inc. is using some of that individualized plant research to help growers on Earth.

Having gleaned important farm-design and plant-growth recipe information from NASA-sponsored research, the company offers contract R&D services for plant-growth optimization, which is handled in its climate-controlled vertical farm in Portage, Indiana. The facility uses proprietary software to adjust conditions and collect plant-growth data. This precise control and measurement make it possible not only to optimize every variable that impacts a plant but also to select plant varieties, known as cultivars, that maintain a particular set of characteristics under specific conditions.

Building on plant data from NASA growth experiments, Green Sense Farm Holdings Inc. of Portage, Indiana, develops and automates optimal growing conditions for plant varieties for Earth-bound indoor farmers.

"We'll look at all of the variables and stressors, trying many different approaches until we optimize the growth of that cultivar in a controlled environment setting," said Robert Colangelo, Green Sense president. One example is testing the ratio of red to blue in LED grow lights, their intensity, and how long they shine in a day.

This approach, based on NASA research, means using only the portion of the light spectrum a plant needs – which also reduces electricity consumption (*Spinoff* 2010, 2018, 2019). And using a closed-loop nutrient recycling system allows for water and nutrient conservation to grow crops sustainably.

Green Sense also developed a technique to suspend the growth of hemp plants to accommodate problems caused by inclement weather on outdoor farms. A set of specific conditions keeps the plants alive and healthy without growing until the weather allows for replanting.

The agency provided the starting point for this research into the specific needs of plant types and tailoring operations to efficiently meet those needs, Colangelo explained.

"You have to conserve everything when you're in space," he said. "So when we built our systems, we built with that in mind. We looked at everything and designed it to have ultimate efficiency to conserve energy."

Green Sense uses LED lights in its vertical farms, adjusting the mix of red and blue light for each plant species. Lane Patterson, chief engineer, examines the successful cultivation of Italian basil. Patterson gained valuable experience in indoor farming when he worked at the South Pole Station, operating an indoor growth chamber that was partly funded by NASA. *Credit: Green Sense Farms LLC*

To convert existing buildings into indoor farms, Bowery Farming Inc. of New York City is leveraging the vertical farm structure NASA originated, along with the expertise of employees who participated in NASA-funded plant-growth research projects.

Redefining 'Data Farm'

Developing these sophisticated growth systems requires data to validate and tweak ideal conditions and catch problems early. What is measured and how is essential to Bowery Farming Inc.'s vertical farms, said Henry Sztul, chief science officer.

The New York City-based company custom-builds urban vertical farms inside existing structures such as vacant warehouses and distributes produce locally to restaurants and grocery stores.

Environmental sensors and cameras throughout the facilities constantly monitor crops and the environment. The company's proprietary system, dubbed the Bowery OS, makes use of machine learning and artificial intelligence to make sense of that data and manage any crop growth cycle.

Just as a person can learn to identify tip burn on a leaf of butter lettuce, computers can be taught the same kind of recognition. Using thousands of pictures taken throughout a farm, computers learn to identify problems and adjust any part of the system, said Sztul.

Scaling up NASA's data-driven vertical growth model to support commercial production required the company to innovate. But NASA has provided additional expertise in an unexpected way – trained staff. Some of Bowery's employees worked on a NASA-funded effort to test plant growth in a simulated space habitat in Antarctica. As students, these employees gained practical experience while demonstrating a remotely controlled closed-loop plant-growth chamber. Several others who worked in NASA's farm at the South Pole Station have also brought that experience to bear in the industry, including the chief engineer at Green Sense Farms.

With three farms in production, Bowery plans to expand to more locations and diversify its crops. But the company is also looking to breed more varieties of current crops that will thrive in a controlled environment. The ability to fine-tune the environment can speed up this breeding program from 10 years to just two or three, explained Sztul.



Plants grown by Bowery Farming using nutrient film technique, a vertical hydroponic system pioneered by NASA, develop a dense root mat that absorbs water, nutrients, and oxygen without using soil. A thin film of water continually flows through the tray underneath the roots, using 2-5% of the water required by plants grown outdoors. *Credit: Bowery Farming Inc.*

Specialized Spuds

Vertical farms aren't the only part of the CEA industry benefiting from NASA growing successes. Potato farmers are now using nutrient film technique to grow seed potatoes in greenhouses. The agency pioneered this hydroponic method to grow root zone crops like potatoes, sweet potatoes, and peanuts, according to Wheeler.

Astronauts won't have the luxury of soil, so NASA developed recipes for hydroponically growing some of these staple crops. This wildly successful technique proved itself with a record-breaking potato yield.

The world record for potato yield is approximately 89,000 pounds per acre. A NASA-funded test in a controlled environment facility at the Wisconsin Biotron Laboratory produced an equivalent of 175,000 pounds per acre, nearly twice the best field-grown yields.

CSS Farms LLC uses the same hydroponic nutrient film practice in its greenhouses to grow seed potatoes, also called minitubers, for customers. The year-round harvesting operation uses many of the same techniques as closed-loop vertical farms – hydroponic growth systems and carefully monitored nutrients customized to the plant variety – but in a less tightly controlled environment that relies on fresh air and sunlight.

Unlike plants grown from seed, such as corn or wheat, potatoes are grown from "seed potatoes" – either cut potato tubers or minitubers that can be

Dramatic greenhouse yields at CSS Farms LLC of Watertown, South Dakota, are the result of a NASA-developed hydroponic growing method specifically for root vegetables such as potatoes.

grown using hydroponics in greenhouses. These minitubers can easily be shipped and then planted in field settings, where they grow into potato plants that produce large tubers for consumption or processing (*Spinoff* 2000).

Using NASA's techniques, CSS, now a Colorado Certified Seed Potato Grower, gets impressive yields.

"We'll harvest two or three times a week for about a 12-week harvest period in three crops per year. In a nutrient film system, you can get anywhere between 30 and 50 minitubers per plant," said Matt Barrow, greenhouse general manager at the company, which is headquartered in Watertown, South Dakota, but has operations across about 10 states. Conventional growing methods using a potting soil mix typically yield five or six minitubers per plant.

Eating Like Astronauts

Long-duration space explorers will benefit from this kind of fresh produce, whether during an extended stay on the Moon or a three-year round trip to Mars. The same is true for people on Earth, where climate change and population growth already cause food insecurity for many communities.

"We need to get much smarter as a society to determine what crops should be grown outdoors and which should be grown indoors," said Colangelo. He likened the use of vertical farming to a supplemental approach to field farming, just as greenhouses have become an integral tool for the world's food supply.

The industry is growing, but progress is slow. Unlike conventional farms, controlled environment agriculture operations don't receive federal subsidies. So individual businesses rely on private investment and sales to grow and become profitable.

Leafy greens that grow quickly and are in high demand, such as lettuce, kale, and spinach, are now the staple crops. As more fruits and vegetables are added and profits increase, the industry can continue to expand.



The fruit and greenery of potato plants are poisonous to humans, but the tubers that grow on the roots are a staple crop around the world. CSS Farms cultivates minitubers that will later be used in field farming to grow the potatoes we buy in grocery stores. *Credit: CSS Farms LLC*

Until then, the U.S. Department of Agriculture (USDA) "has no specific regulation regarding controlled environment agriculture yet," said Tianbao Yang, of the department's Agriculture Research Service (ARS), adding that the fledgling industry's self-imposed tight controls have prevented safety from becoming a major issue.

However, the USDA-ARS has organized a committee to help plant scientists understand how to effectively and consistently use controlled environment technology.

This resource, accessible to both private industry and educational institutions, also includes the growing expertise developed at the space agency.

"NASA researchers have made a great deal of contributions on optimizing plant growth under controlled environments," Yang said. "For example, my research has benefited from their research on light effects on vegetable growth and plant response to stresses."

As NASA continues to make advances through experiments on the space station and in ground facilities to develop an astronaut life-support system, these innovations will continue to support the growth of the controlled environment agriculture industry. ●

NASA Helps Private Lander Shoot for the Moon

Astrobotic's lunar landing program, launching in 2022, carries NASA and commercial payloads



Lacus Mortis (Lake of the Dead) is about 223 miles across with a lot of flat area. This nearside landmark on the lunar surface will be the landing area for the first Astrobotic commercial lunar lander, named Peregrine. Credit: NASA

Autonomous robots building the shelters and other structures astronauts need before they even land is an exciting idea, but is it practical? Testing such a venture on Earth won't prove it can be done on the Moon: up there, dust might interfere with machine parts and low gravity influences performance. However, a realistic test will take place when Astrobotic's Peregrine lands on the Moon.

Companies that NASA started working with in 2014 will send the first U.S. landers to the Moon since Apollo. One of these, Astrobotic Technology's Peregrine lander, is due to launch in 2022 – and its payloads include a crew of mini-robots, owned by another company, which will attempt to coordinate their actions as a group.

Peregrine and other commercial lunar landers will enable more cost-effective and frequent trips to the Moon, rapidly advancing science and other endeavors, making the lunar surface accessible to more investigators.

The Lunar Cargo Transportation and Landing by Soft Touchdown (CATALYST) initiative, run out of NASA's Marshall Space Flight Center in Huntsville, Alabama, aimed to develop an industry capable of taking payloads to the Moon, similar to the way private companies now resupply the International Space Station. After vetting each applicant's strategic vision for providing commercial delivery service, NASA entered into a non-reimbursable Space Act Agreement to mentor each of the selected fledgling companies.

Astrobotic, based in Pittsburgh, was one of three companies chosen. The company engineered its own designs, leveraging NASA engineering assistance and advice, as well as access to space agency facilities and testing resources.

With Peregrine, Astrobotic is making a return on NASA's in-kind investment.

'The Last Step Is a Doozy'

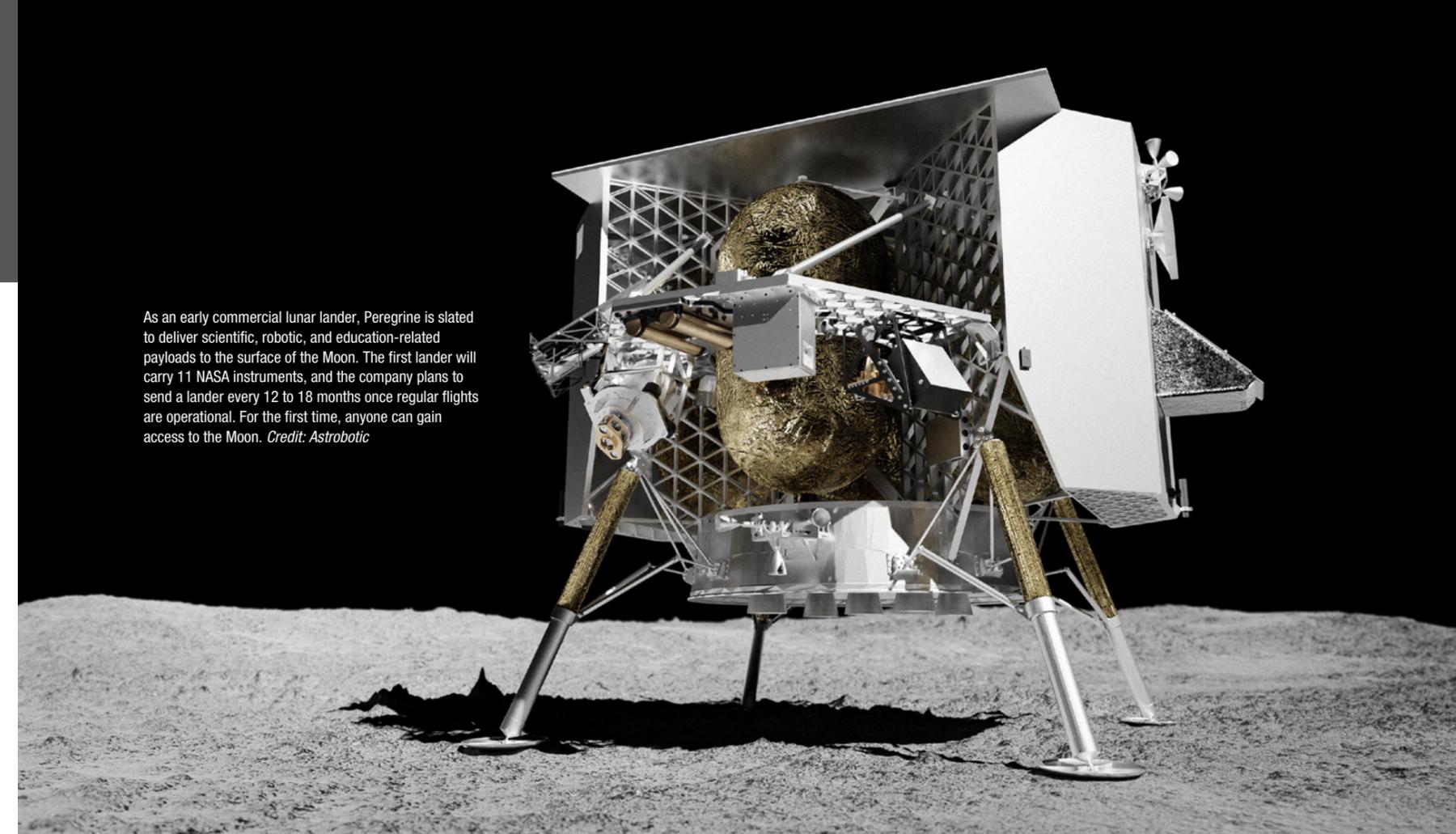
The Peregrine Mission One payloads integrated by Astrobotic include technology, science experiments, and memorabilia from seven different countries. Among those paying to send their items to the Moon are academic institutions, commercial companies, private individuals, and space agencies – including NASA.

To help fund the new landers by buying space on them for agency payloads, NASA also developed the Commercial Lunar Payload Services (CLPS) initiative. A group of NASA's payloads bound for the lunar surface, called task orders, went to Astrobotic.

"We're not managing the mission, that's up to a commercial company," said Chris Culbert, manager of the CLPS initiative. That means NASA is trading a higher degree of risk for a lower cost.

As the lead for CLPS at NASA's Johnson Space Center in Houston, Culbert said contracting commercial services in a new environment will include some failure. He pointed out that we have witnessed failed attempts in lunar landings.

Astrobotic Technology of Pittsburgh leveraged NASA expertise to develop one of the first commercial lunar landers, planned to deliver agency science and technology payloads in 2022. Private organizations and individuals are also sending payloads as space exploration becomes more accessible to everyone.



As an early commercial lunar lander, Peregrine is slated to deliver scientific, robotic, and education-related payloads to the surface of the Moon. The first lander will carry 11 NASA instruments, and the company plans to send a lander every 12 to 18 months once regular flights are operational. For the first time, anyone can gain access to the Moon. Credit: Astrobotic

"We are very confident all of them will launch. We are pretty confident all of them will get to the Moon," Culbert said. "But we tell people, the last step is the doozy."

However, by serving as an "anchor customer," NASA is giving Astrobotic and others the opportunity to succeed. The agency's \$79.5 million CLPS award adds 11 scientific instruments and technology demonstrations.

Going Back for More

Peregrine will land near Lacus Mortis, a region near the equator of the Moon.

"There are plenty of satellites in Earth orbit that are commercially developed, but nothing past that," said Sharad Bhaskaran, Astrobotic's Peregrine mission director. "Our goal is to prove that you can go beyond Earth orbit and land on the Moon using a commercial vehicle."

Among the 17 organizations sending payloads on the company's first mission are:

- Iris rover and MoonArk – examples of human achievement from Carnegie Mellon University (U.S.)
- Scientific instrument from Agencia Espacial Mexicana (Mexico)
- Asagumo rover for scientific and commercial exploration by Spacebit (U.K.)
- Artistic works by students at Balko Public School (U.S.)

And that crew of autonomous robots will try to prove a concept NASA has long considered – sending mobile robot teams in advance of human missions to the Moon and Mars. The trial could also make this option available to spacefaring companies.

"We are very confident all of them will launch. We are pretty confident all of them will get to the Moon. But we tell people, the last step is the doozy."

Chris Culbert, Johnson Space Center

Peregrine will rely on another NASA-supported technology to land – a propulsion system that uses a thruster designed by Frontier Aerospace Inc. The soft landing will help ensure all the payloads safely reach the lunar surface and provide essential performance data. This technology demonstration, developed with Tipping Point funding from NASA, will provide the data necessary for Astrobotic and Frontier Aerospace to develop commercial products to support successful future space exploration. And they will pay off for NASA since the agency plans to use the data for future lunar missions.

Setting the Standard

This will be the first of many flights the company makes, an unprecedented schedule of return trips to the Moon.

“Our goal is to be able to fly a lander once every year or 18 months,” said Bhaskaran. “When scientists get data back from Mission One, they can use that to modify the experiments. A year or so later, they can fly again, making the return on the science much faster.”

For a few lucky scientists, sending an experiment to the Moon still seems like a once-in-a-lifetime opportunity that carries tremendous pressure for success. And the scope of potential research on this first mission is necessarily narrow because it's still demonstrating basic robotic lander technology. But more frequent, regular flights will support more diverse and expansive experimentation.

Researchers and companies will also be able to influence future lander destinations, so these missions can help expand knowledge about the Moon and its connections to Earth. Further landing and payload support technology development will be necessary for that research, and that evolution will also speed up as commercial flights become more frequent.

Astrobotic has also developed the ability to deploy satellites in two different orbits around the Moon. In addition to gathering more lunar data, satellites can add to our understanding of our solar system.

Dan Hendrickson, vice president of business development for the company, explained that the uniformity of the lander infrastructure will make it easier to prepare payloads.

“Every mission isn't going to be boutique,” he said. “We can have the same type of vehicle going over and over again, which will enable lower prices.”

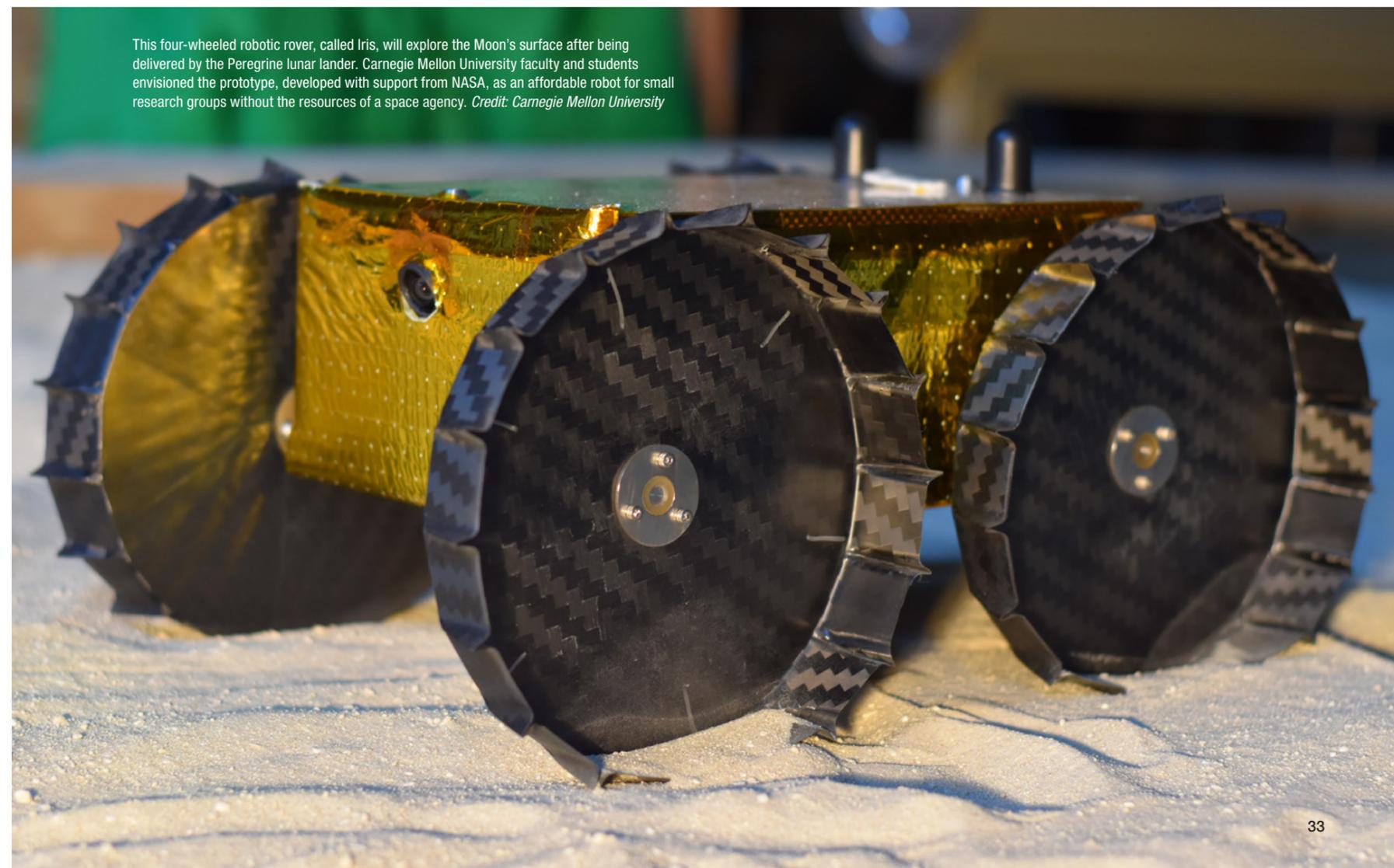
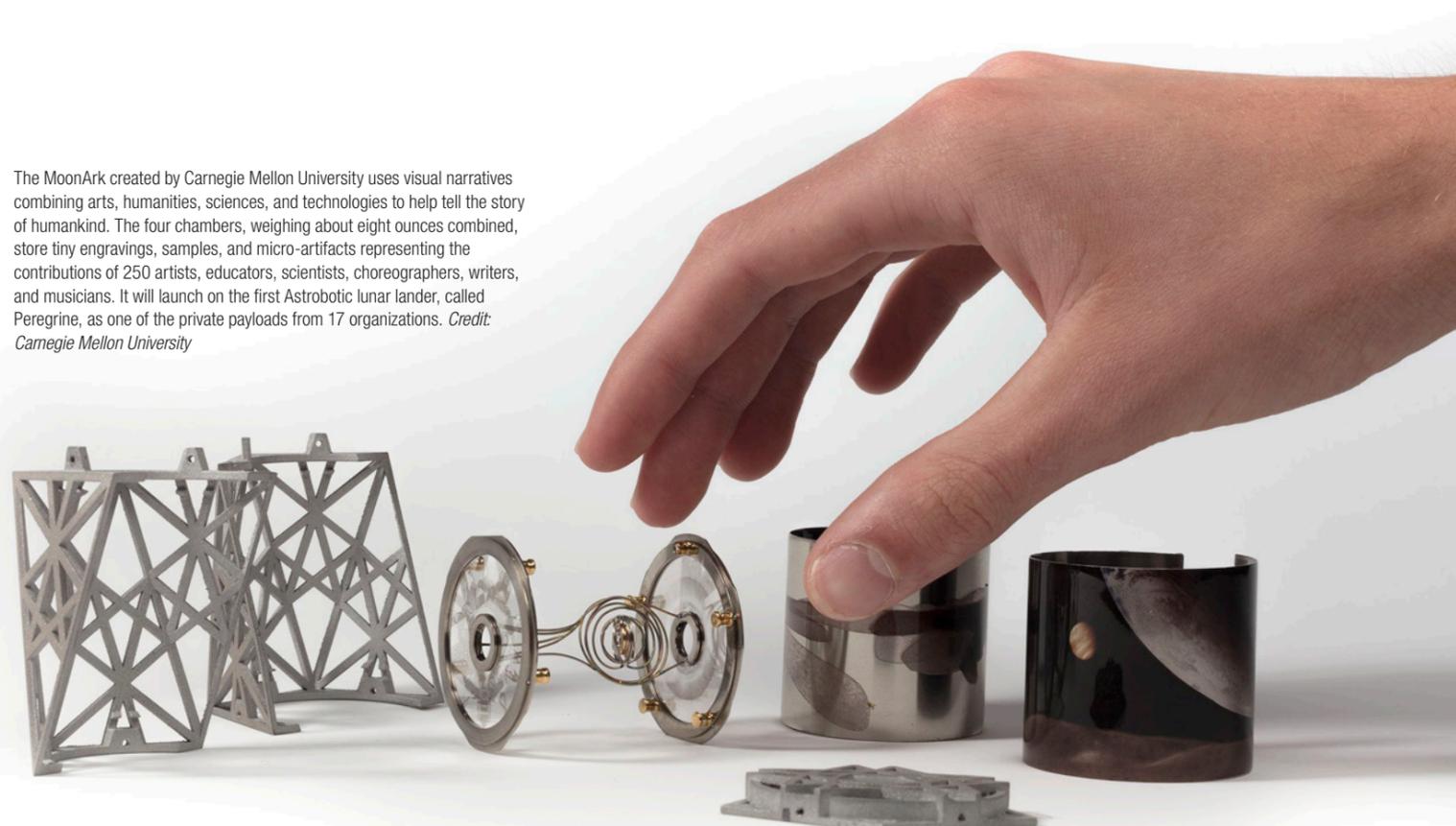
Astrobotic is already planning and accepting payloads for its third lunar lander, tentatively scheduled to make the journey in 2023. Hendrickson credited NASA with extending its spirit of ingenuity to the transition of these payload services to the private sector.

“It took a lot of vision on NASA's part to take on this new approach,” he said. “It's a new way of doing business, and it's exciting to be a part of this.” ●

“Our goal is to prove that you can go beyond Earth orbit and land on the Moon using a commercial vehicle.”

*Sharad Bhaskaran,
Astrobotic Technology*

The MoonArk created by Carnegie Mellon University uses visual narratives combining arts, humanities, sciences, and technologies to help tell the story of humankind. The four chambers, weighing about eight ounces combined, store tiny engravings, samples, and micro-artifacts representing the contributions of 250 artists, educators, scientists, choreographers, writers, and musicians. It will launch on the first Astrobotic lunar lander, called Peregrine, as one of the private payloads from 17 organizations. *Credit: Carnegie Mellon University*



This four-wheeled robotic rover, called Iris, will explore the Moon's surface after being delivered by the Peregrine lunar lander. Carnegie Mellon University faculty and students envisioned the prototype, developed with support from NASA, as an affordable robot for small research groups without the resources of a space agency. *Credit: Carnegie Mellon University*

NASA Helps Drones Take Flight

The agency has helped develop the foundational technology and systems that are enabling remotely piloted aircraft to fill our skies

At the height of the pandemic in 2020, amid stay-at-home orders, social distancing requirements, and uncertainty about how COVID-19 spread, some residents of San Mateo and Contra Costa counties in California began receiving mask and hand-sanitizer deliveries by drone.

The service involved a licensed drone pilot driving a package to its destination by land and then flying it into a customer's backyard on a small, remote-controlled aircraft, without letting it out of sight.

The experiment offers a taste of a future in which remotely piloted and autonomous aircraft will play a much bigger role in people's lives, likely performing a variety of tasks, from package delivery and disaster response to infrastructure maintenance and more.

NASA has been a key player in developing the technologies and systems that will enable aircraft to do these jobs without onboard human assistance. The agency's work helped make the Contra Costa experiment possible. It has also helped companies develop systems to avoid mid-air collisions, and it has created numerous platforms to enable companies to test their own drone technologies.

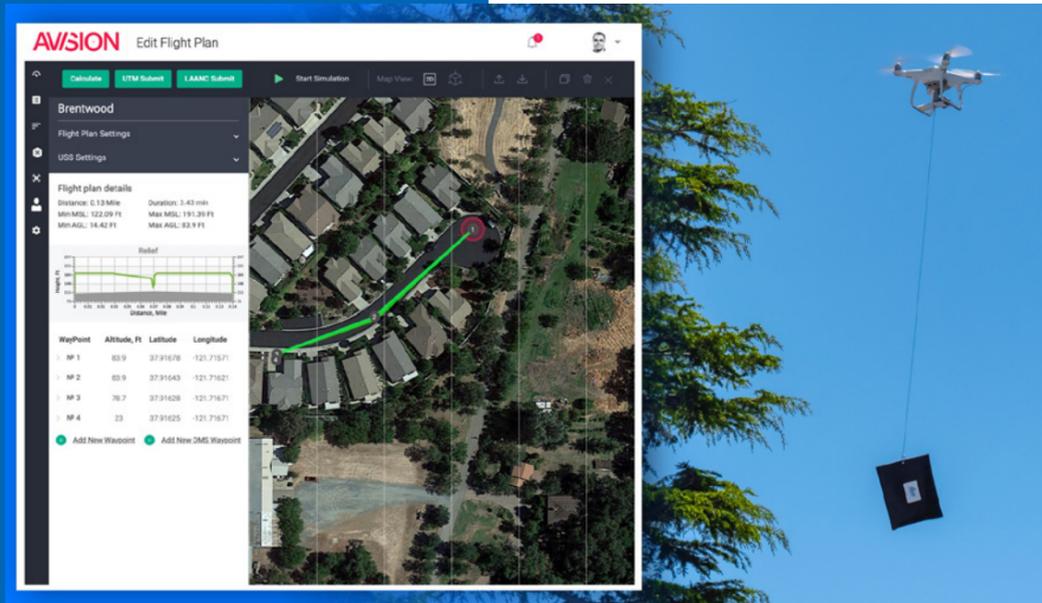
The delivery service in Contra Costa, provided by Dive Delivery for a small fee, used an airspace management app for drones developed by Santa Monica, California-based Avison, one of more than 70 companies that worked with NASA on the now-concluded UTM (or Unmanned Aircraft Systems Traffic Management) project to help small drones use low-altitude airspace regularly, safely, and efficiently, eventually beyond a pilot's line of sight.

Avison joined the project early, in 2015, flying in multiple flight tests under a non-reimbursable Space Act Agreement with NASA's Ames Research Center in Silicon Valley, California. The company went on to develop its own drone management software that communicates with the Federal Aviation Administration (FAA) to help small-drone pilots navigate low-altitude airspace.

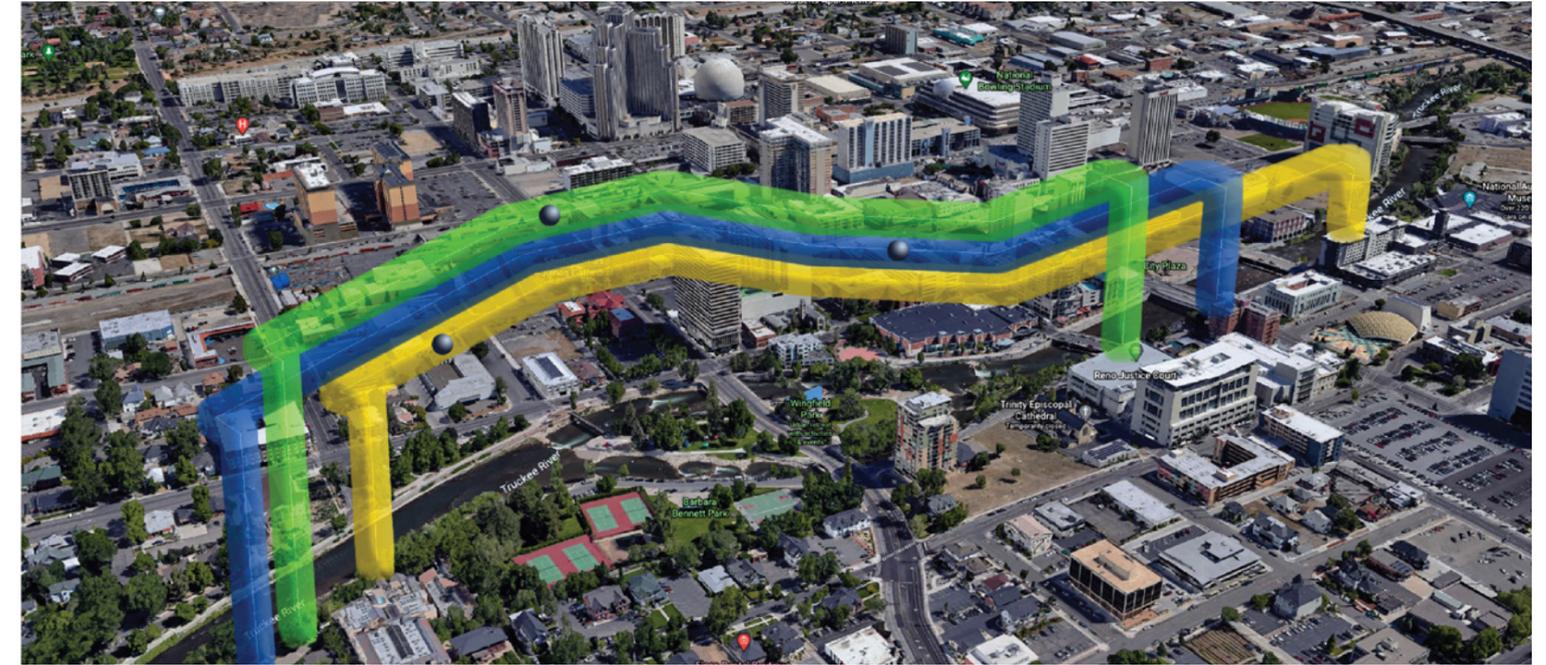
After working with engineers at NASA under a Space Act Agreement, Santa Monica, California-based Avison Inc. developed its own drone management app to help pilots navigate small drones in low-altitude airspace.

"Any FAA-certified pilot or hobbyist can use our app to fly a drone in large parts of the country," said Jim Broniec, Avison's vice president of business development.

"If there are restrictions in your area, we indicate that through the program," he said. "If there's a strong gradient change in the landscape that's going to affect your craft's battery life for a particular flight, our architecture sees and reports this information, intuitively using color-coded indicators of battery life for the drones in an organizational fleet."



After working with NASA on drone management projects, Avison developed its own software to help drone pilots map and report their flight paths. The technology was put to use at the height of the pandemic, when some residents in Southern California received drone deliveries of masks and hand sanitizer to their backyards. Credit: Avison Inc./Dive Delivery



Avison's software communicates with and receives information from the Federal Aviation Administration (FAA) to ensure small-drone pilots have real-time information about the low-altitude airspace they're flying in. The company worked with NASA on the now-concluded UTM (or Unmanned Aircraft Systems Traffic Management) project and on another project to incorporate drone management into disaster response. Credit: Avison Inc.

Avison is also working with NASA to incorporate drone management into disaster response. In situations where hurricanes or wildfires, for example, have damaged infrastructure, remotely piloted drones can help replace a traditional communications system, according to Joey Mercer, a research engineer at Ames who is leading the Scalable Traffic Management for Emergency Response Operations project known as STEReO.

Working on the project to help emergency responders communicate during fast-moving situations has also informed Avison's drone management app, Broniec said.

Starting from Scratch

While developing the technology and systems to enable small, low-flying drones to navigate populated areas, NASA has also been working to incorporate large, remotely piloted aircraft into skies that are already crowded with traditional planes with onboard pilots.

In 2012, a colleague approached computer scientist César Muñoz at NASA's Langley Research Center in Hampton, Virginia, about a new project.

Called UAS in the NAS, the project aimed to help incorporate large (as big as a Cessna aircraft, at least) unmanned aircraft systems (UAS) into the National Airspace (NAS). (The project was concluded in September 2020.)

"We were going to start from scratch," Muñoz said, recalling the conversation with Langley research engineer Maria Consiglio.

"She said we'd start with the requirements, meet with the standards organizations, and start working from the very basics," he said.

Indeed, one of the first tasks was to define what "well clear" should mean for large drones. In traditional aircraft, onboard pilots are required by federal regulations to take specific steps to identify other aircraft in their vicinity and avoid mid-air collisions. "See-and-avoid" measures, as they're called, instruct pilots to keep "well clear" of other aircraft.

For large drones, the team developed a "detect-and-avoid" – instead of "see-and-avoid" – formula to help both conventionally piloted and remotely piloted aircraft achieve the new "well clear" standard without in-person visuals. They had to

decide what kind of alerts pilots on the ground should get and what maneuvers the aircraft should perform to keep clear of other aircraft.

(To this day, there is still no agreed-upon definition of "well clear" for small drones.)

Muñoz then wrote a collection of algorithms for a detect-and-avoid system that complied with all the formulas accepted by the standards agencies. Eventually, the code became open source, and the standards organizations listed it as an example implementation of the requirements for detect-and-avoid systems.

"This is not code that developers directly use in their commercial systems," Muñoz said. "This is code that they can use to test if their systems behave in the way they're supposed to behave. This is for validating."

Companies developing their own detect-and-avoid systems can run a series of tests to ensure their software returns the same results as Muñoz' code, which is called DAIDALUS, for Detect and Avoid Alerting Logic for Unmanned Systems.



A detect-and-avoid system developed by General Atomics Aeronautical Systems gives situational awareness to pilots of remotely piloted aircraft, alerting them to nearby traffic and offering real-time guidance to remain “well clear” of other aircraft. The system will fly on the company’s newest remotely piloted aircraft, the MQ-9B SkyGuardian, pictured here. Credit: General Atomics Aeronautical Systems Inc.

While helping NASA develop detect-and-avoid algorithms that eventually validated new safety standards, San Diego-based General Atomics Aeronautical Systems Inc. developed its own system to help aircraft, including drones, avoid collisions.

DAIDALUS demonstrated that the requirements, which are published by RTCA, a private, not-for-profit organization founded in 1935 as the Radio Technical Commission for Aeronautics, are in fact achievable as they are written and do result in a safe system that enables drone operation.

Remotely Piloted and Global

A key early partner in the DAIDALUS project was San Diego, California-based General Atomics Aeronautical Systems Inc. The company began working with NASA on detect-and-avoid technology in 2014 and soon after started running flight tests at NASA’s Armstrong Flight Research Center in Edwards, California.

The tests involved pilots remotely flying aircraft from the ground.

“We would actually have several displays and algorithms running at the same time – our display, DAIDALUS, and a couple of displays from NASA Ames,” said Brandon Suarez, technical director at General Atomics.

Suarez and his colleagues fed data to all the algorithms, asking pilots to run the scenarios several times with the different displays. “Through all of this human-in-the-loop simulation and flight testing, where we had our prototype system next to DAIDALUS, we learned a tremendous amount,” Suarez said.

“There was a lot of collaboration back and forth between the researchers at Langley – with people like César Muñoz and Maria Consiglio – and our team, from a research perspective,” Suarez said. “We were comparing techniques, comparing algorithms and performance and results, and that all contributed to making a better product.”

General Atomics’ detect-and-avoid system has flown for several years on the company’s MQ-9 (a large remotely piloted aircraft), including for the Air National Guard in an arrangement announced in 2020. The system will also fly on the company’s newest remotely piloted aircraft, the MQ-9B SkyGuardian.

Another version of the company’s detect-and-avoid system is in the process of getting authorization from the FAA for civil use. That will open up the system and the drones that use it to a much wider range of commercial purposes, such as surveying infrastructure like railroads, pipelines, or high-voltage power lines. The detect-and-avoid-system-equipped aircraft will also likely help map and survey land.



General Atomics tested its detect-and-avoid system, pictured here, at NASA, using the agency’s Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) software. Credit: General Atomics Aeronautical Systems Inc.

Suarez noted that, from a global perspective, having DAIDALUS as an example algorithm that meets the requirements has given credibility to the standards themselves.

“The global market is really important,” Suarez said. “If you build large aircraft, you have to be able to operate them in Europe, Asia, and around the world. So having recognition from the international community is a critical piece of the technology development.”

“Because DAIDALUS was open source and because it was included in the technical standard, we were able to develop a product we can sell and that our customers can operate around the world,” Suarez said. “That’s critical for us.”

On the Ground and in the Cloud

Sean Calhoun, managing director of Beaver Creek, Ohio-based CAL Analytics, began working with DAIDALUS as part of the committee that was setting the standards for detect-and-avoid systems. Calhoun and his company were working on a detect-and-avoid system for the Air Force.

“We compared DAIDALUS to some of the algorithms the Air Force was working on, just trying to understand different behaviors and timing and characteristics of the different algorithms under the same type of conditions,” he said.

More recently, CAL Analytics has been working on the civilian side to develop detect-and-avoid services for small drones in the National Airspace.

Smaller drones don’t have the power to carry the most advanced sensors and other equipment to detect and avoid other aircraft, so CAL Analytics’

service shifts the bulk of these functions to ground-based equipment and cloud-based processing.

“Our service doesn’t require any additional equipment on the aircraft,” Calhoun said. “It’s all hosted in the cloud, so we can scale up almost infinitely.”

The detect-and-avoid system pulls in surveillance from other services, like radars and sensors on the ground. Information about the aircraft comes directly from the aircraft itself and from services that – like Avison, the airspace management app maker that enabled drone deliveries – are authorized to share real-time airspace information between drones and the FAA.

“We do all the computation on the ground and push that data to the vehicles for an automatic execution through that UTM network,” Calhoun said.

“A lot of our expertise and knowledge was grounded in and built from the work we did with DAIDALUS and understanding what the appropriate behaviors are,” he added.

Beaver Creek, Ohio-based CAL Analytics LLC’s commercially available detect-and-avoid system for drones was informed by the company’s work testing an Air Force detect-and-avoid system against NASA algorithms.



NASA’s Jim Chamberlain (retired) and a pilot work through a mission scenario with a set of NASA-developed detect-and-avoid algorithms known as DAIDALUS. The CAL Analytics team was visiting NASA’s Langley Research Center to observe an unofficial evaluation of the system. Credit: CAL Analytics/Sean Calhoun

Samantha Smearcheck, then of CAL Analytics, and Bridger Newman, of the Air Line Pilots Association, during Langley flight testing. Credit: CAL Analytics/Sean Calhoun



General Atomics has worked with NASA on detect-and-avoid technology since 2014. The partnership was initially based on the idea of using NASA's Ikhana drone – a version of General Atomics' MQ9 remotely piloted aircraft acquired by NASA and pictured here – as a test bed equipped with the company's prototype detect-and-avoid system and compared to NASA's DAIDALUS algorithms. *Credit: General Atomics Aeronautical Systems Inc.*

Simulations, Live Flights, and Flight Simulators

To ensure they're safe and reliable, detect-and-avoid systems and other technologies necessary for more widespread use of drones all need to be tested. And tested. And tested some more.

As part of the UAS in the NAS project, NASA engineer Jim Murphy and his team in the Aviation Systems Division at Ames developed a flight test environment that includes both real and simulated aircraft in a virtual space. With the Live Virtual Constructive-Distributed Environment, or LVC-DE for short, developers can be sure their systems work in a virtual environment before moving to partial and then full real-world testing with live aircraft.

"We were developing an infrastructure to test these technologies, starting with simulation and building toward flight tests," Murphy said. "The detect-and-avoid algorithms don't know what's live and what's virtual because our environment merges all these different data streams."

General Atomics connected to the LVC-DE when the company was testing its detect-and-avoid system at Armstrong. Through LVC-DE, NASA and General Atomics were able to connect test aircraft at Armstrong with simulation facilities at Ames and test aircraft at a General Atomics facility near Palmdale, California.

Another company, Yorkville, New York-based AX Enterprize, began using the environment in coordination with NASA at Griffiss International Airport, one of seven FAA-designated drone test sites. The woman-owned company provides drone flight and testing support, in addition to communications, data, security, and other services.

Initially, the collaboration with NASA studied pilot reactions in the constructive environment. AX pilots worked on equipment at Griffiss that connected to the environment at NASA, where inputs came from Ames and Armstrong.

To physically connect the networks and resources between the sites, AX received additional funding and support from the space agency to get the required permissions and clearances, known as "authority to operate."

AX improved the LVC-DE, adding a set of tools, models, and live data feeds to help assess drone technologies and to study pilot reaction to the information the system was providing.

The enhanced system could receive and integrate data from actual drones and flights with onboard pilots, as well as simulated flights with simulated pilots, and simulated flights with real pilots. Telemetry and radar alerts provided the pilots with situational awareness, while the ability to link back to a command-and-control post enabled pilots to engage both the live and simulated platforms.

After helping NASA develop a drone flight testing environment that incorporates both live and virtual aircraft, Yorkville, New York-based AX Enterprize LLC continued to enhance the system so its own customers could continue to use it.

"When the aircraft got within some delta that was considered a conflict, the pilot had to react," said AX cofounder M.C. Chruscicki. "The software actually gave the command, instructing the pilot to divert to coordinates it provided."

The combination of simulated and live flights could exercise a detect-and-avoid algorithm appropriately, NASA's Murphy said. "The algorithm can't just cheat," he said, explaining that a poorly designed system might direct a drone to always turn right to avoid a collision, a maneuver that couldn't work with more aircraft in the airspace.

"You need to have the virtual traffic for safety and for cost effectiveness, so you don't have all the vehicles live and flying," he said.

Eventually, NASA stopped updating the LVC-DE and made the system open source for anyone to use. AX continued to use the platform and added more enhancements. The company has used the environment in detect-and-avoid work with Johns Hopkins University's Applied Physics Lab and the Air Force Research Lab.

The enhanced LVC-DE is also part of the more general flight test services the company offers.

"That's exactly what we were hoping industry would do," said NASA's Murphy. "We wanted people to take the technology that we built and then use it, because it provides a mechanism for essentially what we used it for: bringing many different data sources into one interface, and then distributing those data sources to whatever system wants it."



A drone is launched as part of a beyond-visual-line-of-sight element at an FAA-NASA event hosted by AX Enterprize. *Credit: AX Enterprize*

Beyond NASA's Line of Sight

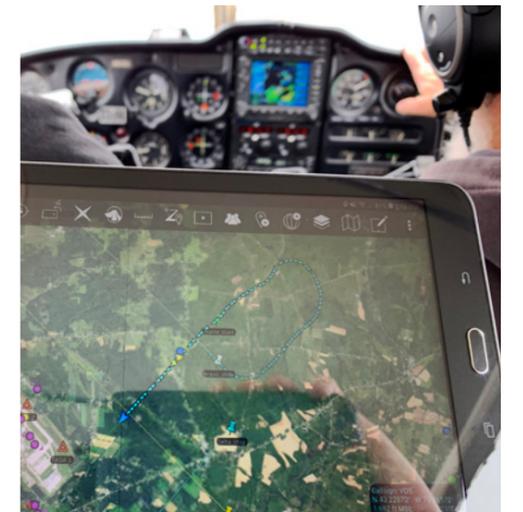
Remotely piloted and autonomous flights are increasingly aiding long-duration scientific research, firefighting, aerial photography, land and crop surveys, pipeline monitoring, border protection, and disaster management.

NASA has helped to lay much of the groundwork for these capabilities and for a future in which remotely piloted and autonomous aircraft will play a much larger role in our lives, whether seen or unseen.

Once they can safely integrate into the airspace, NASA expects drones to transform commercial aviation, likely spurring economic growth and job creation.

"We like to think that we help give these folks a forum in which to figure out what these systems need to do," said Joey Rios, chief technologist in the Aviation Systems Division at Ames, discussing his work with the drone traffic management app maker Avision.

The hope is that companies can then go off and commercialize the knowledge they've gained, he said. ●



A tablet computer screen shows drones and other live and simulated platforms (colored dots) in the airspace near Griffiss International Airport, where AX Enterprize conducts flight tests using a NASA-developed testing environment. *Credit: AX Enterprize*

Space Pens, Pencils, and How NASA Takes Notes in Space

The real story behind the iconic Space Pen and how NASA testing helped it soar

The Space Pen has captured the American imagination in more ways than one. It's appeared repeatedly in pop culture and even worked as a plot device in a "Seinfeld" episode titled "The Pen," and in 2021 it was inducted into the Space Technology Hall of Fame. It's also the subject of a myth that the space agency spent millions to invent a pen that can write in zero gravity, while cosmonauts simply used a pencil.

So, what's the truth? Let's get to the facts about the Space Pen, pencils in space, and how NASA astronauts write on the space station.



U.S. astronaut Walter Cunningham writes with a Fisher Space Pen during the flight of Apollo 7, the first crewed Apollo flight and the Space Pen's first trip to space. The pens have been used on every crewed NASA mission since. *Credit: NASA*

Is the Space Pen a real thing?

Yes, it is. The Fisher Space Pen made its television debut in October 1968, as Apollo 7 mission commander Walter Schirra demonstrated weightlessness by blowing on a pen to control its movement as it floated about the capsule. It was one of the first live video transmissions from an American spacecraft. Since then, Space Pens have appeared in television shows from "Mad Men" and "Gilmore Girls" to "How It's Made." The pens are on display not just in space museums but also in the permanent collection of the Museum of Modern Art in New York. In 2021, the technology was recognized by the Space Foundation as an innovation developed for space that now improves life on Earth, joining around 80 other technologies in the organization's Hall of Fame.

Why not just use a pencil?

NASA wanted to avoid pencils because the lead could easily break off and float away, creating a hazard to astronauts and sensitive electronics on the spacecraft. In fact, a pencil is such an impractical alternative in space that cosmonauts also have been using Space Pens since 1969.

Did it cost taxpayers millions?

Nope. Paul Fisher at the Fisher Pen Company had already been working on a pressurized pen. That said, it would never have reached the heights it did, in orbit or in popularity, without NASA's testing.

"The original ballpoints were terrible," said Cary Fisher, Paul's son and current president of the company, which is now located in Boulder City, Nevada. He noted that the early ballpoints tended to leak, skip, and dry up.

To solve the problem, his father, who had already invented the first universal ink cartridge refill, was working on a sealed cartridge with pressurized nitrogen at the top pushing a tiny piston against the ink. But the pressure caused the pens to leak.

When NASA reached out to him looking for a pen that didn't require gravity, he knew this pressurized ink cartridge could do the trick – if he could solve the leaks. With NASA's interest spurring him on, he finally succeeded when he added resin to the "thixotropic" – almost solid until friction with the ball at the point of the pen liquefied it. He called the result the AG7, for art sent several to NASA.

NASA's Manned Spacecraft Center, now Johnson Space Center in Houston, tested the pens extensively. The pens worked in all positions, in extreme heat and cold, and in atmospheres ranging from pure oxygen to vacuum. And they held enough ink to draw a solid line more than three miles long – well beyond NASA's half-kilometer (.3-mile) ink requirement.

That testing accelerated the pen's development from a prototype to a proven high-performance product.

Once it had flown in space, Paul decided on the name Space Pen. "I thought it was a terrible name," his son recalled. "I said it's going to sound like a toy. But my father was right, as he often was."

The pens are known in part for their reliability, but they also came to symbolize American ingenuity: at a time when NASA was struggling to overcome countless obstacles to put astronauts on the Moon, an inventor and small business owner stepped up and solved the pen problem.

Paul and his son continued perfecting the technology and designing new models.

Do astronauts still use them?

The pens have been used on every crewed NASA mission since Apollo 7 – dozens are currently on the International Space Station.

Is it only for space?

The Space Pen line now comprises about 80 models.

While they are popular gift items, Cary said, they are especially in-demand among members of the military and law enforcement, as well as outdoor enthusiasts, plane manufacturers, and oil workers, all of whom, like astronauts, appreciate their ability to write in any conditions.

Fisher Pen Company has distributors in 52 countries but still makes all its pens in Boulder City, where more than 60 employees turn out over a million pens a year. ●



Fisher still sells its original AG7 model, the very first Space Pen. *Credit: Fisher Pen Company*



Fisher Pen Company founder Paul Fisher celebrates the company's 50th anniversary, displaying various models of the Space Pen he invented. *Credit: Fisher Pen Company*

Boulder City, Nevada-based Fisher Pen Company accelerated development of a pressurized ballpoint to meet NASA's need for a pen that could write in zero gravity. NASA tested the resulting pen rigorously. The Space Pen has flown on every crewed mission since Apollo 7 and become a popular gift item on Earth.



The pen celebrating the 50th anniversary of the Space Pen, shown here open and closed, is one of Fisher's Bullet model pens. *Credit: Fisher Pen Company*

Forecasting Saharan Dust to Minimize Health Risks

NASA-funded system uses satellite data to predict timing and severity of African dust storms in the Caribbean

In the summer of 2020, wind carried nearly 24 tons of dust from the Sahara Desert in Africa across the Atlantic Ocean, to North and South America, hitting islands in the Caribbean Sea especially hard.

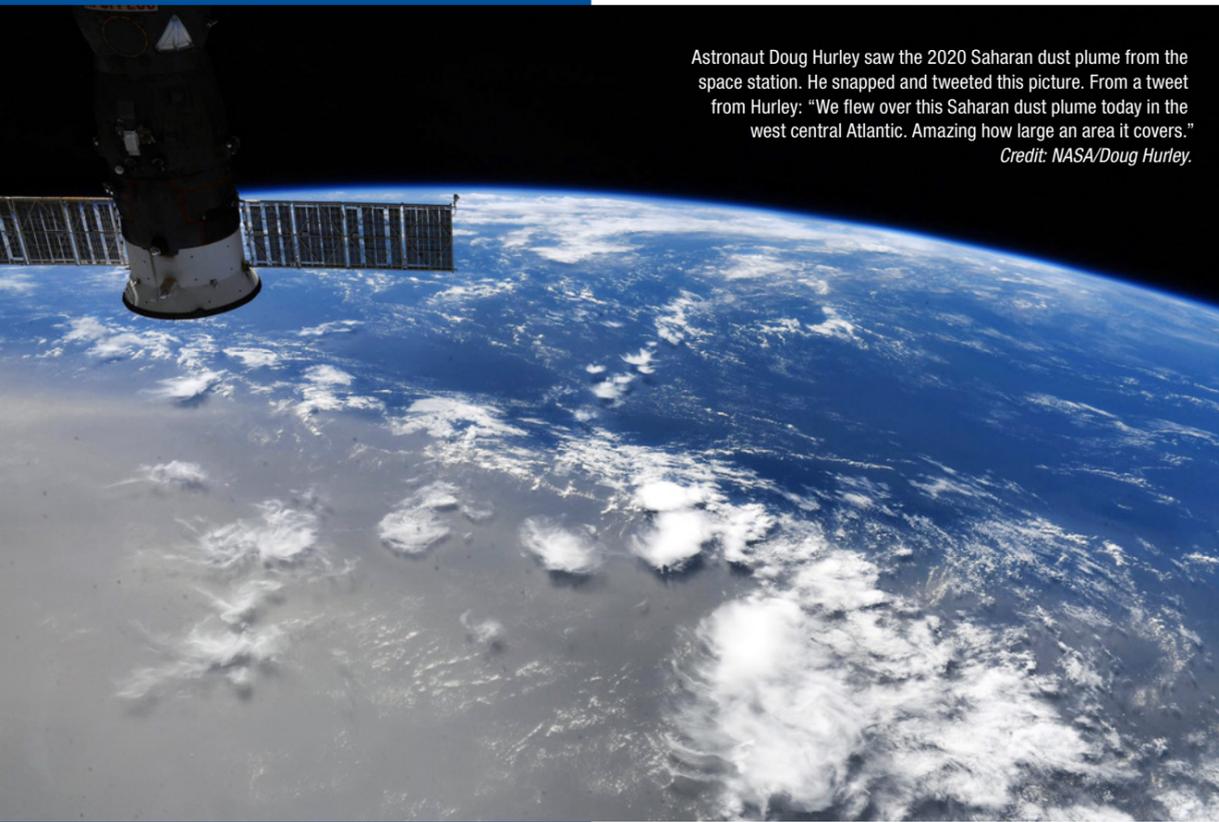
It was one of the largest Saharan dust storms on record, and it came in the middle of the global pandemic. An early warning system for African dust was developed with NASA funding and put in place in Puerto Rico just days before the event. Through this tool, for the first time, citizens across the island received advance notice that the dust storm was coming.

“We were monitoring a couple of different NASA models and satellite images,” said Pablo Méndez-Lázaro, an associate professor at the University of Puerto Rico Medical Sciences Campus in San Juan, who led development of the warning system.

“As soon as we saw the dust storm, we started communicating the news,” he said. “We got in contact with corresponding government agencies and collaborating medical doctors.”

Saharan dust clouds make this journey every year, helpfully fertilizing soil with phosphorus and other nutrients. The right amount of dust feeds Caribbean coral, but too much can cause algae overgrowth. It can also irritate people’s eyes, ears, noses, and throats with fine particles of silica and other minerals that can infiltrate lung tissue, aggravate sensitivities, and reduce visibility.

Astronaut Doug Hurley saw the 2020 Saharan dust plume from the space station. He snapped and tweeted this picture. From a tweet from Hurley: “We flew over this Saharan dust plume today in the west central Atlantic. Amazing how large an area it covers.”
Credit: NASA/Doug Hurley.



“During the summer of 2020, as in many other places, we were also struggling with COVID-19,” Méndez-Lázaro said, “and COVID-19 is a respiratory virus. We were very concerned with how the dust could exacerbate the symptoms.”

Early Warning, Better Preparation

The Saharan dust warning system involves monitoring satellite data, gathering samples, and alerting government agencies and the public, giving people time to prepare.

The 2020 dust storm, nicknamed Godzilla, was so big that astronauts on the International Space Station could see it.

Méndez-Lázaro and his team use an array of NASA tools and sensors to track aerosols – which can include liquids, gases, bacteria, viruses, and

NASA-funded researchers at the University of Puerto Rico in San Juan use satellite data to track dust and other aerosols traveling across the Atlantic Ocean from the Sahara Desert. They alert local and federal governments and the public in advance of poor air quality.

volcanic ashes, in addition to dust – mostly with NASA’s Visible Infrared Imaging Radiometer Suite, or VIIRS, onboard the Suomi-NPP (National Polar-Orbiting Partnership) satellite.

The VIIRS instrument enables researchers to determine aerosol optical depth, an indicator of the amount of aerosols in the atmosphere.

“It could be a bunch of different things, so the satellite information is not enough to know what kind of aerosol is up there,” Méndez-Lázaro said. “But because of the trajectory of the dust cloud, you know where it’s coming from, and from the ground-based sampling, you know where it was born.”

The additional path and origin information enables scientists to confirm that a cloud is, in fact, Saharan dust, which can help them predict its effects.

Several days before the 2020 storm, Méndez-Lázaro’s team held a Facebook Live event with one of Puerto Rico’s top meteorologists, Ada Monzón, reaching an estimated 300,000 viewers. Méndez-Lázaro also spoke about the hazardous atmospheric conditions on another Facebook Live broadcast by the National Weather Service – San Juan.

Monzón and other meteorologists included the information in their forecasts, so the public and especially vulnerable groups – including the elderly, children under 5, pregnant women, and people with asthma or other respiratory or dermatological issues – could take precautions and avoid being outside.

Méndez-Lázaro and his team also provided visualizations through a tool that they planned to make public-facing. Based on the warnings, the Puerto Rico Department of Health Office issued public health recommendations. The advance warning from the satellite data also enabled the system’s ground samplers to prepare to quickly analyze and characterize the dust, which caused two days of unhealthy air conditions in Puerto Rico.

Better understanding of the dust can help doctors treat patients suffering from its health effects, especially if the dust is carrying pathogens, and it enables the researchers to retrospectively analyze the initial satellite data for possible improvements in future forecasts.

Earth Observations on Earth

Méndez-Lázaro and his team developed the warning system with funding from a three-year NASA Applied Sciences grant awarded in 2019. All proposals were peer reviewed.

By the time the storm came in 2020, an early version of the warning system was in place for Puerto Rico. Méndez-Lázaro and his colleagues have been working to expand it to the U.S. Virgin Islands as well.

The team is currently establishing a sustainable partnership with CARICOOS, the NOAA Caribbean Coastal Ocean Observing System, to keep the system in place after the NASA funding ends.

Méndez-Lázaro received additional NASA funding in 2020 to investigate how the Saharan dust plumes and other environmental factors affect the spread and severity of COVID-19.

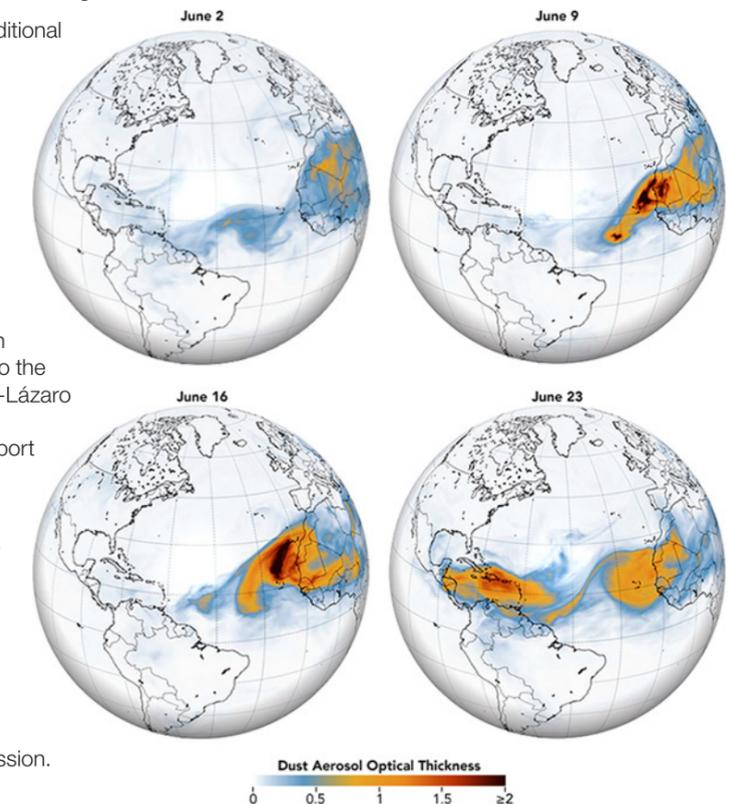
“We were concerned that people already struggling with the virus could get worse and their symptoms more severe because African dust is another aggravation to the pulmonary system,” Méndez-Lázaro said. His team continues to analyze data and plans to report preliminary findings on this issue in the near future.

John Haynes, who manages Health and Air Quality applications in the Applied Sciences Program in the Earth Science Division at NASA Headquarters in Washington, said Méndez-Lázaro’s work is a perfect example of his program’s mission.

“Our mandate is to discover and demonstrate innovative and practical uses of Earth observations,” said Haynes, who served as the NASA-side technical officer on both projects.

Terabytes of Earth data are downloaded every day from NASA’s constellation of Earth-observing satellites. This information is used to answer basic scientific questions about how Earth systems are changing. Then NASA’s Applied Sciences Program aims to get that information into the hands of people who make forecasting and policy decisions, so those decisions can be quicker or better.

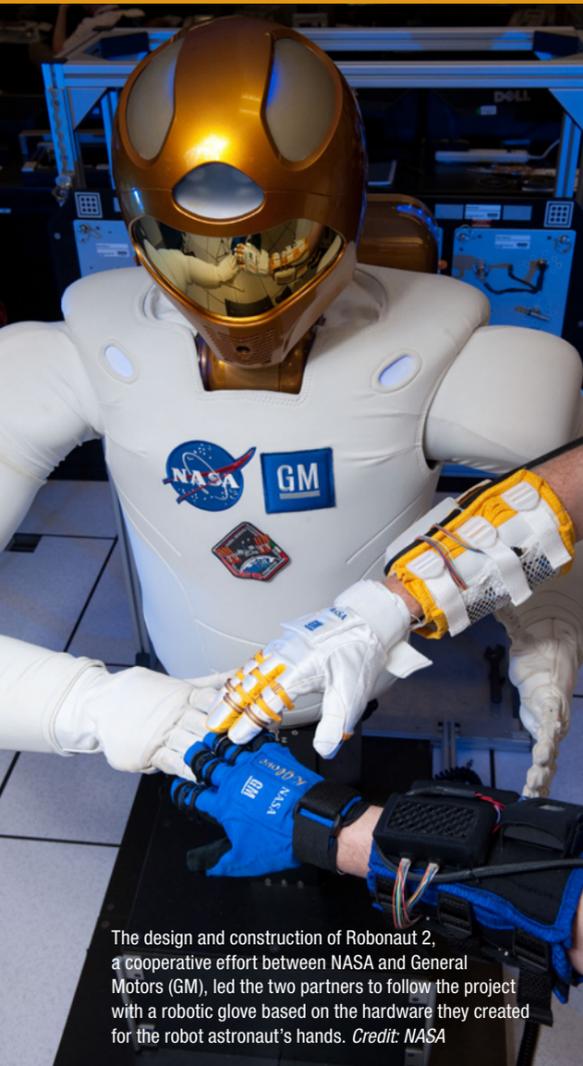
“Pablo and his team are not only harnessing optical-depth data from VIIRS, but also ground observations,” Haynes said. “They’re assembling that information and providing it to other agencies in useful formats so they are able to make better decisions when these dust storms are forecast to occur.”



In 2020, for the first time, scientists were able to alert Puerto Ricans to an imminent threat to air quality from African dust, thanks to an early warning system that was put in place just days before one of the largest Saharan dust storms on record. Pictured here are pulses of Saharan dust at one-week intervals from June 2-23, 2020, as they made their way across the Atlantic Ocean, based on data from NASA’s Goddard Earth Observing System (GEOS) modeling system. Credit: Joshua Stevens, NASA

NASA's Robotic Glove Finds Commercial Handhold

Grip-strengthening glove based on robotic astronaut assistant aims to reduce workplace stress injuries



The design and construction of Robonaut 2, a cooperative effort between NASA and General Motors (GM), led the two partners to follow the project with a robotic glove based on the hardware they created for the robot astronaut's hands. *Credit: NASA*

It's no coincidence that our most complex, versatile, and useful body part, the human hand, is also among the most prone to injury. With its fine motor and sensory coordination, delicacy, and strength, the hand also sets a standard for robotics engineers to strive for, being supremely useful and still impossible to replicate.

A person, for example, can effortlessly reach a hand into a pocket and fish out a dime from among a multitude of other coins and little objects, a feat no robot can match, noted Jonathan Rogers, a mechanical design engineer at NASA's Johnson Space Center in Houston. "The human hand and forearm is a marvel of capability for its size."

So it's no surprise that one of the biggest obstacles to creating the first robot astronaut to fly in space was building its hands. Nor is it surprising that the hands were the first aspect of the robot to be commercialized. Factory workers around the globe are now trying out Ironhand, a robotic glove designed to help them perform repetitive tasks without fatigue or injury. There's nothing else like it on the market.

Robots Can Lend Astronauts, Auto Workers a Hand

The world's first industrial-strength robotic glove only exists because NASA and General Motors (GM) realized that space exploration and automobile manufacturing had a lot of common goals. The first was a need for robots and humans to work side-by-side, so they signed a 2006 Space Act Agreement for the construction of Robonaut 2 (R2). This was a faster, more dexterous follow-up to the earlier Robonaut prototype built by NASA and the Defense Advanced Research Projects Agency.

The partnership brought half a dozen GM engineers to Johnson, where they helped design and build the robot that flew to the International Space Station five years later and proved it could perform simple tasks alongside astronauts.

NASA and General Motors joined forces to build Robonaut 2. The work led to a suite of robotic glove patents, now licensed and commercialized by Bioservo Technologies AB of Stockholm, Sweden, for industrial workplaces.



After building the hands for Robonaut 2, both NASA and GM saw potential uses for a robotic glove based on the same hardware. While the automobile manufacturer saw the potential to reduce repetitive stress injuries on factory floors, the space agency's astronauts have always had difficulty using pressurized gloves in space for extended periods. *Credit: NASA*

With that work completed, the team "recognized that we could repackage the finger actuator drive train into a wearable device" that could help both astronauts and auto workers, Rogers said.

Automobile factory employees can become fatigued from performing repetitive tasks, leading to quality control problems and, worse, injuries, Rogers said. These days, partly because robots already do much of the heavy lifting, stress injuries among factory workers are more common in the hands than, for example, the lower back or shoulders.



"Any technology NASA comes up with that benefits society as a whole is a return on taxpayers' investment."

Jonathan Rogers, Johnson Space Center

Jonathan Rogers, now deputy chief of the Robotic Systems Technology Branch at Johnson Space Center, worked with a team of Johnson and GM engineers to build Robo-Glove, a robotic glove that could help manufacturing workers and astronauts alike. *Credit: NASA*

Likewise, hand fatigue has long plagued astronauts working on the outside of spacecraft. In the vacuum of space, an astronaut's suit, including the gloves, becomes a pressurized balloon, stiff and difficult to bend, explained Rogers. So extended work in space can lead to aches and raw spots on the hands and even delaminated fingernails in worst-case scenarios.

The team understood that a glove could provide grasping strength to solve both problems. So once an R2 model was safely aboard the space station, the NASA and GM team started building robotic gloves based on the hardware in the robot's hands and forearms. For the space agency, having a partner that could both provide an industry perspective and help secure patents was a big help, Rogers said.

Glove Technology Finds Its Fit

By 2015, GM workers were trying out prototypes known as Robo-Glove. The company began looking for a commercial partner to further refine the technology and found that Robo-Glove was not the world's first robotic grip-strengthening glove. Two years earlier, the company Bioservo Technologies of Stockholm, Sweden, had released its Soft Extra Muscle (SEM) glove, intended to compensate for hand injuries.



Swedish company Bioservo Technologies' Ironhand, based on a set of patents from NASA and GM's Robo-Glove, is the world's first industrial-strength robotic glove for factory workers and others who perform repetitive manual tasks. *Credit: Bioservo Technologies/Niklas Lagström*

“They eventually chose us because no one else had a similar product on the market,” said Martin Wahlstedt, development director at Bioservo. The company licensed six Robo-Glove patents from NASA and GM and got to work, with GM testing prototypes as they were built.

“Because we were a medical device company, we had to learn a lot about industrial applications,” said Mikael Wester, the company’s marketing director.

By 2018, other partners were testing the first release of Bioservo’s Ironhand, including Airbus, General Electric, and the French construction and infrastructure giant Eiffage. Based on feedback, the company refined its Ironhand 1.6, released in 2020, when it was named NASA Commercial Invention of the Year, along with Robo-Glove.

Most Ironhand sales are still for trial runs, but the company is planning a larger commercial rollout. Two companies, Rhino Assembly Corporation and Alpha Quantix, have signed on to distribute the device to U.S. manufacturers. Other partners are distributing it in Europe.

Wester said feedback from users has been overwhelmingly positive, especially from those with preexisting hand injuries, and Wahlstedt said some workers have reported that they were able to stop using pain medication.

“We have users who don’t want to let go of it after the trial,” Wester said.

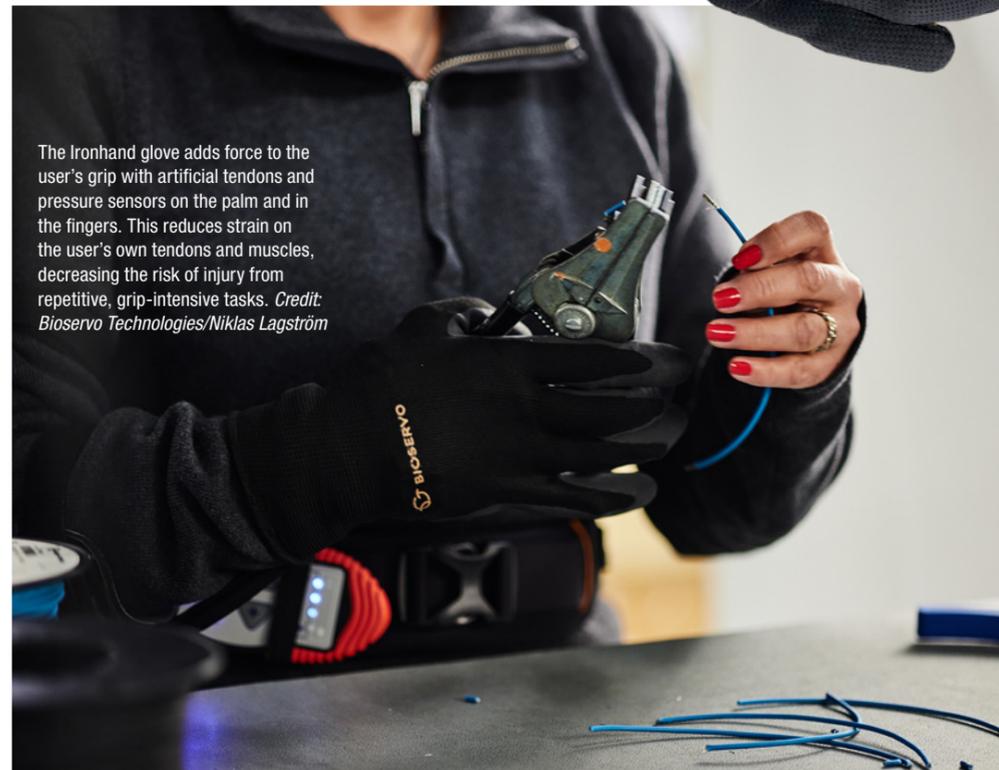
While robotic exoskeleton devices have emerged as a field in the last five years or so, this is still a new frontier, said Wahlstedt, and no one else has put out an industrial grip-strengthening glove, not least because it’s a difficult engineering feat. “A traditional approach with beams and hard structures can’t be applied to the hand. The hand is very complex in its anatomy, and how you use it is also complex and varied.”

“We have users who don’t want to let go of it after the trial.”

Mikael Wester, Bioservo Technologies



Bioservo Technologies released the second version of its industrial robotic glove, Ironhand 2.0, in June of 2021. The glove connects to a power pack worn in a backpack or hip-carry. *Credit: Bioservo Technologies/Niklas Lagström*



The Ironhand glove adds force to the user’s grip with artificial tendons and pressure sensors on the palm and in the fingers. This reduces strain on the user’s own tendons and muscles, decreasing the risk of injury from repetitive, grip-intensive tasks. *Credit: Bioservo Technologies/Niklas Lagström*



Musculoskeletal disorders are among the most common occupational injuries, with most of them in the arms and hands, and they’re a major cause of long-term sick leave. Ironhand was created to both reduce these injuries and help workers recovering from them. *Credit: Bioservo Technologies/Niklas Lagström*

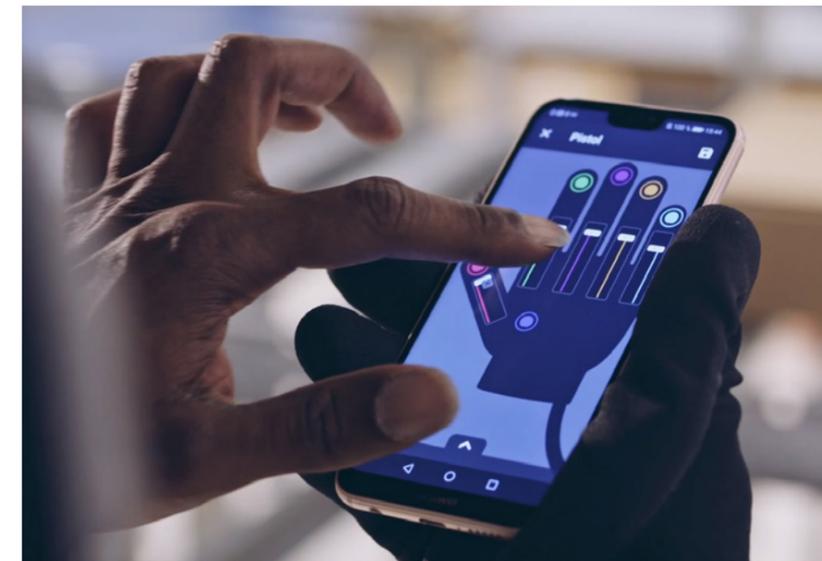
The company, which started in 2006 with a neurosurgeon and a mechatronics professor who initially wanted to help patients with limited hand functionality, now has two commercial products – Ironhand, for industrial use, and Carbonhand, for medical use. In the last two years, its workforce has grown from eight to 28 employees, largely jumpstarted by the Robo-Glove collaboration with GM, said Wahlstedt.

The Next Robots for Earth and Space

Meanwhile, after NASA’s partnership with GM ended, Rogers, now deputy chief for Johnson’s Robotic Systems Technology Branch, led a two-year effort to adapt the technology for spacesuit gloves, leading to two pending patents the agency plans to offer to Bioservo. “It’s a huge win that came out of the glove,” he said. “Any technology NASA comes up with that benefits society as a whole is a return on taxpayers’ investment.”

Johnson engineers are now building on technology from R2 and Robo-Glove with another commercial partner, an Australian natural gas company interested in deploying robots for dull, dirty, or dangerous field jobs. NASA plans to use advances made under the project for robots to maintain the planned lunar Gateway outpost, which will only intermittently house astronaut crews.

Code written for motor control, manipulation, and autonomy can be applied to a variety of robots, noted Rogers. “Those core enabling technologies can be carried over from R2 to whatever we come up with.” ●



The Ironhand glove can be adjusted to user preferences and task-specific motions, with combinations of force, sensitivity, finger balance, and locking tendency saved as profiles and controlled with the IronConnect Pro app, shown here, or a remote control worn on the chest. *Credit: Bioservo Technologies/Niklas Lagström*

Safely Detoxifying Soil and Groundwater with NASA Technology

Revolutionary iron emulsion created an eco-friendly alternative to costly site decontamination

At 5:12 a.m. on Sept. 28, 1982, a train derailed near Livingston, Louisiana, waking residents nearby to the sound of explosions and raging fires. What the residents didn't see until later were the thousands of gallons of toxic chemicals – 27 train cars' worth – soaking the ground, polluting soil and groundwater alike.

The town spent millions of dollars, and more than 30 years, using well-known remediation techniques to attempt to clean up the spill, but the toxic chemicals remained at levels high enough to keep the area perennially on the Environmental Protection Agency's list of "brownfields," or contaminated properties.

In 2013, the town was ready for something new. It turned to a unique environmental remediation technology first created at NASA in 2002 to safely destroy chemical contamination left over from the early days of the space program.

Called emulsified zero-valent iron (EZVI), the formula has become one of the space agency's most far-reaching success stories (*Spinoff* 2005, 2010). The two related patents have been licensed more than a dozen times by private companies, which have in turn cleaned up contamination across the United States and around the world.

This innovative technology has made it possible, for the first time, to eliminate chlorinated chemicals left deep in soil and aquifers by dye and paint manufacturers, dry cleaners, chemical manufacturers, metal cleaning and degreasing facilities, electronics companies, pharmaceutical manufacturers, and more.

October 2021 marked a significant milestone as the technology turned 20 and the patents expired, leaving behind a significant legacy of companies that have successfully manufactured the technology for more than a decade.

Mini-Bioreactors

"If you're aware that you may have any potentially contaminated sites, by law you're required to go investigate," said Jackie Quinn. An environment engineer at the time with NASA's Kennedy Space Center in Florida, Quinn also served as the project lead for EZVI development.

The law she was referring to was the 1976 Resource Conservation and Recovery Act, which prompted NASA's review of potentially hazardous sites. One such site was Kennedy's historic Launch Complex 34, where thousands of gallons of chlorinated solvents had soaked into the ground during the Apollo program. Chlorinated solvents, which NASA used to clean rocket engine components, were once thought to be harmless but are now known toxins and carcinogens – and are difficult to eliminate.

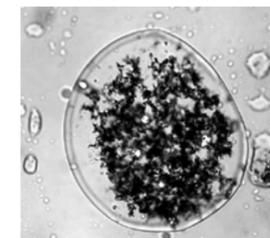
Toxicological and Environmental Associates Inc. of Miramar Beach, Florida, developed SourceKill using a non-exclusive license for NASA's eco-friendly EZVI technology to reduce on-site chemicals to their harmless components.

Only slightly soluble in water, and much heavier, they sink below the water table and settle into tiny cracks and spaces among the rocks and soil, making them virtually impossible to find and remove. They're also persistent, barely breaking down over time. As they mingle with water, they can threaten local wildlife and contaminate drinking water.

So Quinn and Kathleen Brooks Loftin, a NASA analytical chemist at the time and now Kennedy's chief technologist, partnered with the University of Central Florida to find a way to break down these chemicals across a vast area without causing any additional environmental damage. They came up with a combination of emulsified vegetable oil, water, and microscopic iron particles. It was revolutionary.

"We create an oil bubble around a little bit of water with iron in it," explained Quinn. "Each one of those bubbles is like a little micro-reactor." The vegetable oil attracts the hydrophobic chemicals, drawing them in. Concentration gradients then push the toxins from the oil into the water, where the iron spurs a reaction that degrades the molecules into by-products that are expelled from the bubble. Then the process repeats, over and over, for decades if necessary, until no toxins remain.

The Florida sites where NASA and the U.S. Air Force tested the new technology – Launch Complex 34 and nearby Patrick Air Force Base – saw dramatic reductions of contamination within a few months.



A closeup of an emulsified zero-valent iron (EZVI) micell shows the zero-valent iron particles in a water-in-oil emulsion. The metal nanoparticles react with the contaminants, breaking apart their chemical bonds and releasing harmless molecules back into the ground. Credit: NASA



The Saturn 1 SA-4 launch vehicle sits on Launch Complex 34 at NASA's Kennedy Space Center prior to one of many Apollo-era flights. This was also the site of significant soil and groundwater contamination until the agency developed EZVI and safely destroyed the chemicals that had been used to clean rocket engine parts. Credit: NASA

Cheaper, Faster, and More Effective

It was clear EZVI would be useful outside NASA, so the Kennedy Technology Transfer Office jumped into action to get it into the hands of private companies.

Along with the patent license, Quinn showed some early adopters how to reproduce the correct formula. Toxicological and Environmental Associates Inc. (TEA) of Miramar Beach, Florida, the company that brought EZVI to the Livingston site, used the NASA training and insight to scale up the manufacturing needed for thousands of gallons of its EZVI product, called Sourcekill.

The company also had to figure out the best methods for injecting the emulsion into different soil conditions such as sand, silt, and clay.

"The delivery of the EZVI was going to be a big issue," said Brad Droy, CEO of TEA. "How do you get it to effectively distribute throughout the contaminated area?" Over time the company, working with injection experts, developed best practice methodologies for soil mixing in shallow soils and for hydraulic fracturing in silts, clays, and fractured rock.

TEA now both manufactures EZVI for other companies and uses it with its own remediation customers. The company has supplied or injected several hundred thousand gallons of EZVI for

projects in 15 states in the United States as well as Canada, Australia, and Japan.

Applying EZVI can be done in a matter of days or weeks, with positive results seen typically within three to six months, making it far less costly than treatments that can take decades. "This remediation technique destroys the source material that causes the contamination, so it's a cheaper, more effective solution," said Droy.

A non-exclusive license for patented NASA technology that safely removes toxins at a spill site enables Woodard & Curran Inc. of Portland, Maine, to help companies mitigate damage and comply with EPA standards.

'Significant Advance'

EZVI can destroy a variety of chlorinated hydrocarbon compounds such as carbon tetrachloride, tetrachloroethylene, and trichloroethylene. Some alternative decontamination methods require excavating soil and rock for treatment, which can cause major disturbances to the site. These approaches could leave toxins deep underground where excavators can't reach, allowing the chemicals to migrate deeper and farther.



Kennedy Space Center shares its island with the Merritt Island National Wildlife Refuge. More than 330 native and migratory bird species, along with 25 mammal, 117 fish, and 65 amphibian and reptile species call Kennedy and the wildlife refuge home. Credit: NASA

“The innovation of EZVI is the structure of the emulsion,” said Greg Booth, senior technical leader for on-site remediation for the Portland, Maine-based Woodard & Curran. “The NASA patented technology provides the ability to directly contact and destroy the contamination source and continues to be a very significant advance for the industry.”

Booth was one of the first users of the technology, even before joining Woodard & Curran, as part of the team that worked on the cleanup project at Patrick Air Force Base. The goal was to reduce the contaminant source by 50% within 25 years and 100% within 80 years. But after one EZVI treatment, the reduction was close to 90% in just six years. Since then, he’s also worked to advance formulations of EZVI.

Freeport, Illinois-based Provectus Environmental Products Inc. manufactures EZVI for its clients and other remediation companies using a non-exclusive patent license to support the safe removal of chlorinated hydrocarbon compounds from soil and water.

Building on the Recipe

Provectus Environmental Products Inc. in Freeport, Illinois, also manufactures EZVI for its own projects and the environmental remediation industry. The company develops remediation solutions for clients, frequently combining multiple technologies to maximize cleanup efficiency.

“By taking a holistic approach, we’ve found ways to combine biological activity with oxidation and reduction chemistry,” explained Wade Meese, CEO of Provectus.

To date, the company has manufactured EZVI for cleanup projects in 17 states and provided EZVI for Brazil. Whether it’s an electronics manufacturing site in South Carolina or a former dry cleaner in New Jersey, Provectus has used the technology to address soil, groundwater, and bedrock chlorinated solvent contamination.

“NASA did the world a favor by creating the product,” said Meese. “It’s a key component of our business structure, and it gives us another innovative remediation tool to enable a comprehensive solution at complicated sites.”

Beyond the Hall of Fame

In 2005, EZVI was recognized as both the NASA Government Invention of the Year and NASA Commercial Invention of the Year. In 2006, the inventors won the Federal Laboratory Consortium’s Award for Excellence in Technology Transfer. And in 2007, EZVI was inducted into the Space Foundation’s Space Technology Hall of Fame.

Terra Systems Inc. of Claymont, Delaware, uses a non-exclusive license for EZVI to clean up brownfield sites in the United States and overseas.

One of the first license holders, Terra Systems Inc. of Claymont, Delaware, has used the award-winning solution to manufacture and provide EZVI for projects in New Jersey, Florida, and Washington state, as well as projects in Japan, according to Dr. Michael D. Lee, vice president of research and development.

“NASA has been a good partner with reasonable patent licensing terms,” he said.

“We look forward to hearing about more successful usages of the EZVI technology for decades to come,” said Jim Nichols, technology licensing manager for Kennedy.

“NASA is constantly innovating to solve its own challenges and is always happy when the resulting technologies also help solve problems well beyond the scope of aviation and space travel,” he said. ●

Cleaning up the soil and groundwater contamination caused during the Apollo program in and near Merritt Island National Wildlife Refuge was one of many environmental restoration efforts enabled by EZVI. *Credit: Getty Images*

Expertise Flows from Computer Cognition

NASA-grown AI technology enables energy industry innovations

Keeping the lights on in West Africa can be difficult, as the electricity market in the region is plagued with power shortages. While disparities exist, access has improved in the last decade across the region from Senegal to Nigeria. However, according to the World Bank, some 50% of the population still has no access to electricity. In areas on the grid, a report from 2020 found regular blackouts averaged 44 hours a month. Existing power plants in the region are inefficient and expensive to maintain. Expanding access to reliable power would require new infrastructure and adopting new technologies. With a bit of help from NASA technology, artificial intelligence could be one of the keys to solving these megawatt-scale challenges.

A Billion Miles from Tech Support

Modern computers can make billions of decisions per second, but if just one of these decisions is wrong, it could jeopardize an entire space mission. When spacecraft are in the furthest reaches of the solar system, diagnosing one of those problems can be difficult. Because communications are limited by the speed of light, there are several hours of lag between data transmitted and information received. These missions require huge amounts of data to be streamed over limited bandwidth. And project managers are only human, with limited working hours to sift through all the information pouring in. Because of these factors, monitoring for signs of trouble needs a special kind of expert – one that is more machine than human.



Early artificial intelligence (AI) systems helped manage operations of the NASA Galileo mission, which explored Jupiter and its moons. *Credit: NASA*



Artificial intelligence systems to monitor performance of space systems and suggest solutions to issues led Beyond Limits Inc. of Glendale, California, to use software derived from those programs across the entire process of energy production.

Developed in the early 1980s, expert systems were among the earliest artificial intelligence (AI) programs in use at NASA. These systems work similarly to a complex flowchart, using real-time data as their inputs and narrowing down the solutions based on these answers. While deductive reasoning made them useful, these systems required the use of large mainframes to keep track of the knowledge base.

Recognizing that being tethered to a supercomputer made using these systems significantly more complicated, Mark James and David Atkinson at NASA's Jet Propulsion

Laboratory in Southern California decided to build a more compact version of an expert system, the Spacecraft Health Inference Engine (SHINE). James also created a natural language-understanding program called Hunter, powered in part by SHINE.

In 1989, when the Voyager 2 probe was approaching Neptune 12 years after launch, SHINE proved itself when it discovered a glitch in the telecom system that, if not fixed, would have caused a serious loss in communication during the encounter.

SHINE later found use in several space probes and projects at the agency, analyzing telemetry from the Galileo spacecraft that explored Jupiter and its moons in the 1990s and reducing workloads for the Extreme Ultraviolet Explorer space telescope as it searched for white dwarfs and surveyed the sky. But the work done to improve expert systems would find new uses outside of NASA.

Power from Pump to Plug

After NASA developed the program over decades, Beyond Limits of Glendale, California, exclusively licensed both SHINE and Hunter from JPL as a base for its own AI system in 2014. Founded that same year, the company's primary goal is to use artificial intelligence to assist in decision making and planning for projects of any scale.

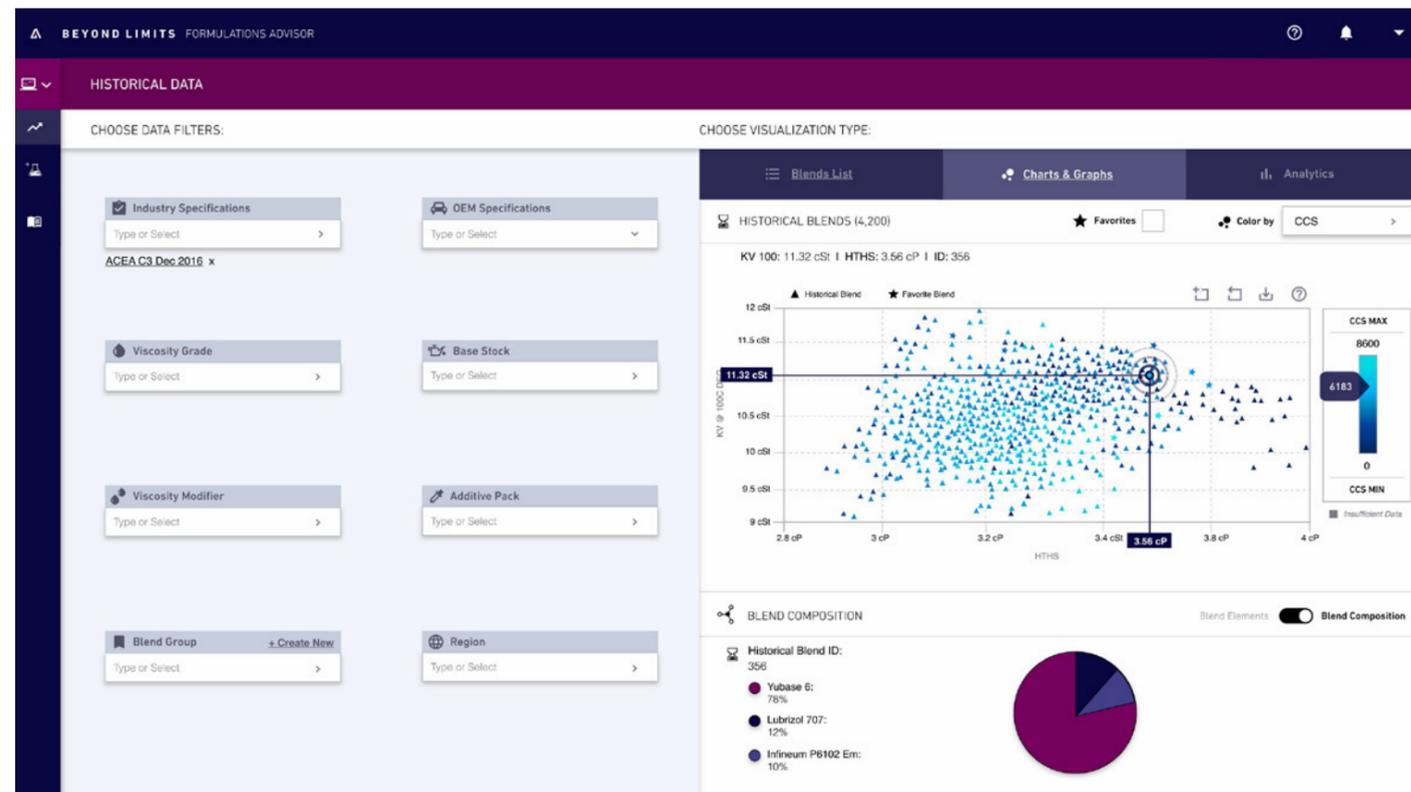
In 2016, Beyond Limits' NASA-derived AI technology was used in algorithms to help online advertisers better reach their intended audiences, but since then the technology has grown considerably (*Spinoff* 2016).

"AI is really agnostic to any specific sector. It can solve a wide range of applications," said AJ Abdallat, CEO of Beyond Limits.

The company has interest from manufacturing firms and healthcare providers. However, one of the largest markets currently is among energy companies, which use the system to help



Beyond Limits' AI, derived from the Spacecraft Health Inference Engine and Hunter expert systems originally developed for NASA missions, will be used in a "cognitive power plant" currently being constructed to serve West Africa's unified energy market. Credit: Getty Images



The Cognitive Formulation Advisor is one of several tools made by Beyond Limits utilizing AI technology to support the energy industry. Credit: Beyond Limits

determine placement of oil wells. By processing data about existing oil fields, Beyond Limits' AI can identify prime locations for new exploration, saving money and time.

"For some of these projects in oil and gas, we're allowing them to reduce timing from months to days, to hours," Abdallat said.

Beyond Limits is also helping to realize improvements after petroleum discovery too, building AI systems that allow companies to construct more efficient refineries as well.

This is not the only part of the energy industry Beyond Limits is invested in. In West Africa's unified energy market, the company is involved in the creation of the first AI-driven power plant with capital investment from Swiss bank Xcell. Abdallat said this new "cognitive power plant" is enabling more efficient generation of electricity from natural gas.

Power plants typically don't keep a lot of electricity storage on-site, with all generated power being sent to the grid and managed at the utility level, which could result in overgeneration and wasted energy. With the assistance of AI, the power plant can actively manage how much electricity comes out of it. When power needs are low, the natural gas plant only fires for as long as necessary. But on a hot day, when all the air conditioners are on and fans are set to maximum, the power needs can be met automatically.

Problem Solving, No Matter the Problem

Since the announcement of the plant in West Africa, Beyond Limits' international operations have seen massive growth. The company has launched business operations in the Asia-Pacific region, with several rounds of investment. Other industries are also working with Beyond Limits to help find solutions in their fields. Water utilities are using it to find leaks in their pipes, and the

company's tools are available on the Microsoft Azure platform for quick deployment in the cloud. In the years since its founding, the company has won several awards for its technology, including in 2020 when it was added to the CB Insights AI 100 list of companies that show promise in the artificial intelligence industry.

The company still maintains a close relationship with JPL and the California Institute of Technology (Caltech), with scientists using Beyond Limits' AI technology to determine optimal placement of scientific instruments, such as black hole detectors, at Caltech. No matter how many fields find uses for its AI, Abdallat said the company couldn't have gotten as far as it did without the initial push from NASA-grown tech.

"We started with a legacy of technology, and we're continuing that legacy." ●

Lasers Make Waves in Self-Driving Cars, Quantum Devices

JPL photonics inventions improve lasers and oscillators for autonomous vehicles, next-generation communications, and quantum computing



NASA's Deep Space Network uses atomic clocks to provide accurate spacecraft navigation at great distances. A team at the Jet Propulsion Laboratory that improved that technology developed new capabilities using quantum physics, which are now part of the basis for OEwaves' laser technology. *Credit: NASA*

Navigating the solar system's vast distances has, paradoxically, required NASA to master the physics of the universe's tiniest particles.

"If you've been flying for six years, and you have just one chance for a Jupiter flyby, and you don't get there at the right time and place, the entire investment you've made is essentially gone," explained Lute Maleki, former researcher at NASA's Jet Propulsion Laboratory in Southern California. "Atomic clocks are what allow you to accurately navigate to your target, and as such they're extremely important."

These clocks calculate time based on the steady vibration of excited atoms, which serve as a clock's oscillator, much like a pendulum in a grandfather clock, but one that swings billions of times per second.

NASA's Deep Space Network (DSN), a sort of GPS system for space, relies on atomic clocks for extreme accuracy. Any modern navigation system must accurately time radio signals to triangulate a location. But the need for accuracy is even higher in space, where great distances can compound even tiny errors.

Advances made by Maleki and his JPL colleagues for space have now led to some of the world's most refined lasers and oscillators for applications like communications, range-finders for self-driving cars, and emerging fields like quantum computing.

Favorable Optics

In the 1980s, as he worked to improve atomic clock technology for the DSN, Maleki established what became known as JPL's Quantum Sciences and Technologies group to develop new capabilities using the quantum physics that govern the most elementary particles, such as photons or the vibrating atoms in a clock. The team developed a better, more affordable type of atomic clock and also, for the first time, sent atomic clock signals through fiber-optic cables to antennas almost 20 miles away.

In the early 1990s, Maleki and another member of his lab ended up inventing a new type of oscillator.

"He had a stability problem he couldn't solve, and I told him to turn it into an oscillator to solve it, and we invented the optoelectronic oscillator," Maleki said.

Oscillators are crucial not only for timekeeping but also for communications, where they let two or more devices agree on a precise frequency at which to send and receive information. While all previous oscillators had used an electric current to generate their vibration, this one used laser light. Maleki's team found that the invention performed better than electronic oscillators, producing low-loss, low-noise oscillation with high efficiency, especially at high frequencies.

The optoelectronic oscillator has since become critical to a number of applications, such as radar, space engineering, and wireless communications.

To ensure a constant frequency, however, the oscillator needs a resonator. At the time, this usually was an optical fiber that could carry an output signal over a good distance – ideally a mile or so – and circulate it back, allowing the system to keep track of its own output frequency and cancel out noise, Maleki explained. It made for a bulky system.

This led to his second foundational invention: the use of a whispering gallery mode optical resonator. The name comes from the observation that a whisper uttered along the inside of the dome of St. Paul's Cathedral in London could be heard on the opposite side because sound waves traveled along the dome without decaying. The discovery had led to spherical resonators in which light waves could circle repeatedly, but little practical use had been made of them.

"What we did at JPL was, we took that, and first we flattened the sphere to make it like a button," Maleki said. "And it has good properties when you do that. And the second thing was that we made it out of these crystalline materials" – magnesium fluoride, calcium fluoride, quartz – "which nobody had done before. We essentially started the entire field of fabricating whispering gallery mode resonators out of material other than glass, as well as their use in new applications, in our JPL group."

Subatomic Physics, Massive Applications

At the time, NASA had little use for it, but Maleki was confident there was a market.

He founded OEwaves (the OE stands for optoelectronic) in 1999 in Pasadena, California, with about 30 patents from his team's NASA work, licensed through the California Institute of Technology, which manages JPL. "Everything we build now really draws on those two basic technologies," he said, referring to the optoelectronic oscillator and whispering gallery mode resonator.

The company took a while to find its footing in a changing technology landscape, but its products, which include the lowest-noise semiconductor lasers available, have found new markets opening up in recent years. One is in "smart structures," a concept that has existed for decades but is beginning to be put into practice, especially in Asia. Fiber-optic sensors embedded in buildings, bridges, railroads, and other structures can sense stress or deformation, but this requires low-noise lasers to reveal tiny variations in wavelength.

Maleki said he also expects increased demand in the cellphone and communications markets, as they move toward higher frequencies, which carry information more efficiently but require extremely high fidelity. He noted that the company's oscillators offer significant performance advantages at reduced size, weight, and power.

And in 2014, OEwaves spun off a company called Strobe Inc. to develop lidar technology for self-driving cars. A lidar system uses

The optoelectronic oscillator and whispering gallery mode optical resonator, created at NASA and licensed to their inventor at OEwaves Inc. of Pasadena, California, have gained widespread popularity and enable high-performance lasers and communication devices for emerging fields.

reflected laser signals to build a three-dimensional map of its surroundings, which many autonomous vehicle companies regard as an enabling technology. GM subsidiary Cruise Automation purchased Strobe in 2017.

Maleki said the same technology that began at JPL allowed Strobe to develop small, efficient lidar systems that were able to rapidly change frequency – a technique called "chirping" – using only the resonator. Chirping helps to measure both the distance and speed of surrounding objects. And the whole system could be put on a photonic integrated circuit, further reducing costs.

A number of universities and companies are also purchasing the laser components to research future quantum devices for communications, computing, and other applications. Maleki noted that several major companies are working towards quantum computers that, using individual atoms and ions, could carry out computations that would take a standard computer longer than the life of the universe. Several are using OEwaves lasers.

Lasers Appear on the Radar

Back at JPL, at least one team is now using OEwaves' technology to push the limits of radar capabilities. A team there developed a prototype for a high-frequency millimeter-wave radar that should give higher-resolution, more accurate information about water vapor in the atmosphere, improving weather models and forecasting abilities.

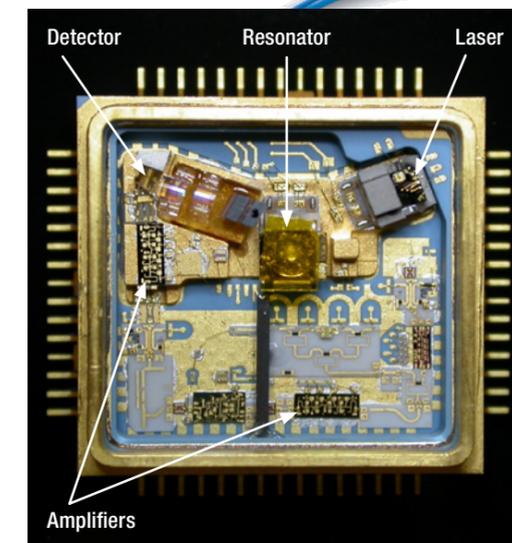
Eric Kittlaus, an optical engineer working on applying optics to the radar development, explained that the team needed an extremely low-noise, high-frequency microwave source, something that is difficult to achieve with conventional electronics. So the team, in collaboration with OEwaves researchers, figured out how to combine two of the company's lasers to directly generate high-frequency microwaves suitable for the planned atmospheric radar.

"Typically, radar is radar, and laser optics is viewed as completely separate," Kittlaus said. "Combining the two different worlds, you can do some very intriguing new things."

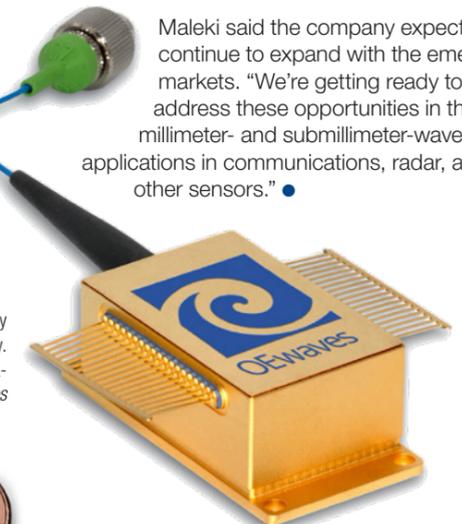
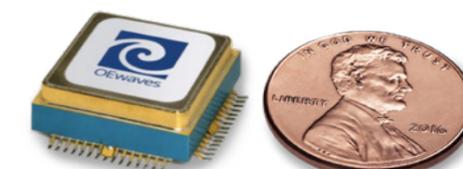
He noted that the technology rests on the exceptional ability of the tiny, crystal resonators to control and trap light wavelengths for extended periods.

Having started out with just a few employees, OEwaves now has a staff of about 30, in addition to the half dozen or so who left to form Strobe. Several employees over the years have come from the JPL Quantum Sciences and Technologies group. The company now holds about 160 patents, including its early JPL licenses.

Maleki said the company expects to continue to expand with the emerging markets. "We're getting ready to address these opportunities in the millimeter- and submillimeter-wavelength applications in communications, radar, and other sensors."



Quantum technology allows OEwaves to produce extremely low-noise, low-loss optoelectrical oscillators the size of a penny. These enable tiny, efficient, high-fidelity devices like the ultra-narrow-linewidth laser at right. *Credits: OEwaves*



Lighting in a Bottle

NASA's lighting research gives people on Earth better rest and helps plants grow

John Glenn's first trip into Earth orbit lasted just under five hours, but today astronauts regularly stay six months or longer on the International Space Station. Experiencing over a dozen sunrises and sunsets each day means an astronaut's biological clock tends to be in the wrong time zone. And for longer deep-space missions, NASA needs to develop ways to grow food without relying on sunlight.

NASA-funded research to understand how light affects humans and plants, however, has had benefits far beyond space. It has helped develop biologically oriented LED technology for everyday life on Earth.



Designed to replace existing fluorescent fixtures, the Solid-State Lighting Assembly (SSLA) was installed on the space station in 2016 and helped astronauts maintain their circadian rhythms. *Credit: NASA*

Lightbulb Moments

From 1997 to 2017, the National Space Biomedical Research Institute (NSBRI) looked into how long-duration spaceflight affected people, funded with grants from NASA's Johnson Space Center in Houston. One area of interest was light sources and how they affected brain activity. The NSBRI funded two professors, Thomas Jefferson University's George Brainard and Harvard Medical School's Steven Lockley, to learn more.

Lockley and Brainard's research found that exposure to excess blue light at the wrong time could throw off a person's body. This happened because the body's production of melatonin, a key hormone for managing circadian rhythms, was inhibited when certain wavelengths of blue light hit photoreceptors in the eyes.

When the fluorescent lighting fixtures on the space station needed to be replaced in 2011, NASA looked to the growing field of solid-state light-emitting diodes (LEDs), and the findings of the NSBRI's research played a big role.

"When NASA started looking into [LED fixtures], the industry didn't even have standards for solid-state lighting. They didn't have any information, certainly not a lot of research on large-scale implementation of circadian lighting," said Toni Clark, testing lead for spacecraft lighting at Johnson.

Researchers there and engineers at NASA's Kennedy Space Center in Florida worked together on the Solid-State Lighting Assembly (SSLA) for the space station. The lamp module was primarily built by Bionetics Corporation, which also had labs and manufacturing facilities on-site at Kennedy. The new lighting modules, installed in 2016, consumed far less energy and emitted far less heat than previous fluorescent lighting on the station. In addition, they changed color, temperature, and intensity in a 24-hour cycle, in accordance with the NSBRI's circadian lighting research.

The change paid off, as astronauts reported feeling better-rested. LED modules also helped in plant-growth experiments on the space station, with the lights providing the right wavelengths for photosynthesis.



Astronaut Andrew Morgan waters plants in the Veg-04B experiment on the space station. This space botany research is one of several studies into how to provide fresh food for crews on long-term space missions. *Credit: NASA*



Engineers who worked on the SSLA went on to work for Lighting Science, which spun off several firms. Healthe continues to make adjustable LED circadian rhythm lights, as well as the Healthe Air sanitization system. *Credits: Healthe*

Headed Home

Lessons learned from the space station lighting modules soon made their way onto the market. After completing the initial system, several members of the Bionetics team moved to another company called Lighting Science to keep working on solid-state lighting.

The company's work with LEDs goes back to the early 2000s. Fred Maxik, the company's CEO, had worked under a Space Act Agreement at Bionetics as an expert on lighting systems. The company developed a wide range of bulbs that reflected the NASA research for human health and plant growth. In 2018, Lighting Science spun off several companies, each developing technologies based on the original circadian LEDs.

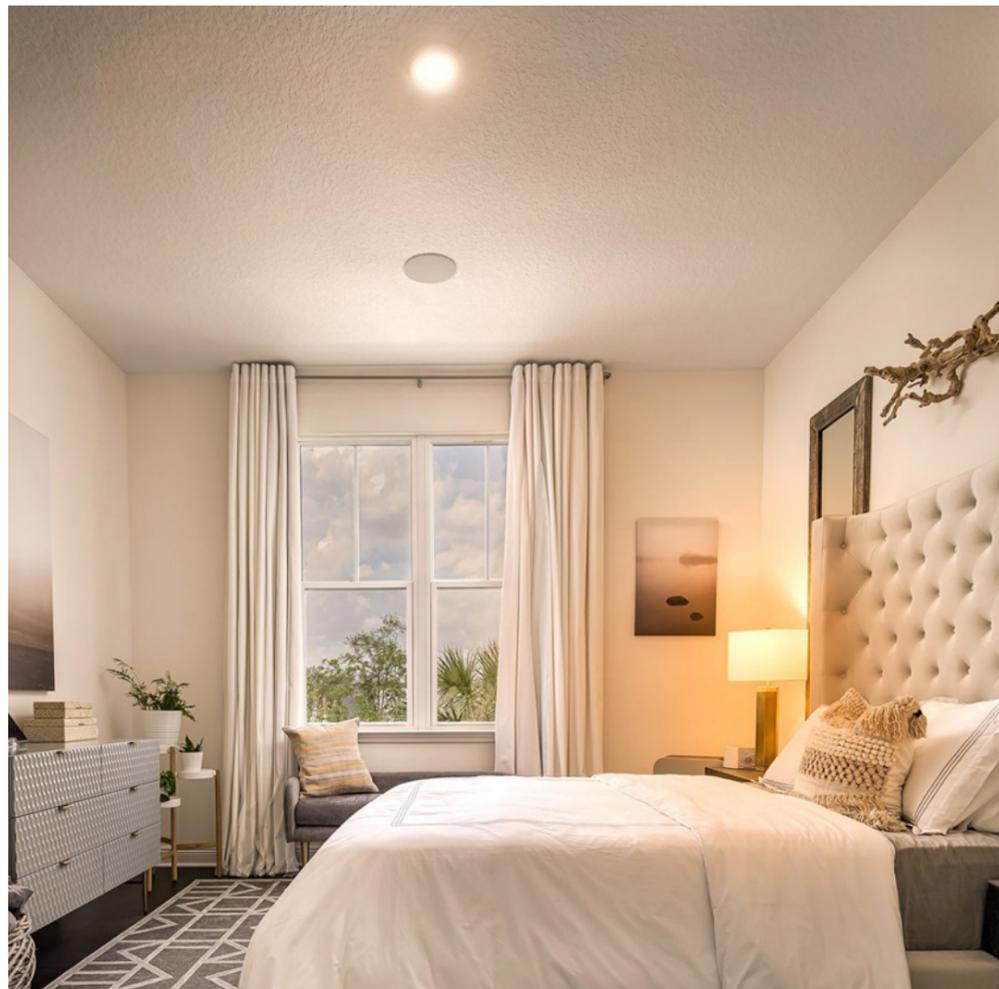
Healthe Inc. of Orlando, Florida, based on experience designing spacecraft lighting for NASA and using NASA-funded circadian research, developed automated LED bulbs to promote healthy sleep-wake cycles. The company further developed the technology into a method of sanitizing air with ultraviolet light.

Healthe Inc. (pronounced "healthy") of Orlando, Florida, was one of the first. The company's primary market is in LED bulbs designed for keeping circadian rhythms in check.

One product line, the GoodDay and GoodNight bulbs, is based off older designs originally made by Lighting Science, specifically tuned to emit wavelengths to induce wakefulness and sleepiness. Another line, called SunTrac, can be paired to an app or an outside light meter that automatically adjusts the light throughout the day.

More recently, Healthe began using its technology to assist in decontamination and air filtration. Designed to fit into a standard ceiling lighting grid, these systems use ultraviolet light, which inactivates pathogens, paired with a fan and filter. Instead of bathing a room in UV light, the units suck in air through an intake and into an internal chamber, where it's blasted with rays in the shortest, most potent range of ultraviolet wavelengths, known as UVC. The air is then filtered before it comes out into the room. NASA has explored this technology for potential use in future spacecraft, but the company was able to leverage the knowledge gained from designing UV-capable LEDs for growing plants in space. Healthe has installed its UV systems in buildings that, since the COVID-19 pandemic started, have been looking to expand their sanitization protocols.

"The bulk of our [decontamination] sales today are to senior living communities," Maxik said. "But we do work with office buildings, schools, anywhere that can support large-scale lighting systems."



LEDs Provide for Plants

Another Lighting Science spinoff that has capitalized on that company's experience working with NASA is VividGro of Chicago, which primarily sells to industrial cultivators.

This technology also has its origins in the LED lighting designed for the space station. Like the space station lighting array they're derived from, VividGro's lamps use specific wavelengths to induce biological reactions in living organisms. Instead of managing human biorhythms, however, they're tuned exactly to the right frequencies to power plant metabolism.

Because LED technology is so efficient, they also use much less energy than other options, consuming just over half that of high-intensity discharge lamps previously used in greenhouses.

The company's FlowerMax line is intended to provide for flowering plants, while the VegMax lights are designed for growing vegetables like lettuce. In 2021, the company was acquired by AgTech Holdings, and its products are exclusively distributed by the controlled environment agriculture company GroAdvisor.

Even after more than two decades of development, Maxik believes there's a lot more that can be done with LEDs.

"This is still an adolescent business in my view," Maxik said. "Saving watts per unit doesn't take into account all the other properties we can associate with light. We can now manipulate that freely and use it to help people." ●

Building on experience from working on circadian and grow lamps for NASA, VividGro of Chicago developed solid-state LED technology into more efficient grow lights for indoor agriculture.



Plants flourish under certain kinds of light, so LED systems made by VividGro provide the right kind of lighting for industrial cultivators of plants and vegetables. *Credit: GroAdvisor*



NASA has done several experiments with growing plants in orbit on the space station. The Veggie system uses LEDs to provide the kind of light that plants need. *Credits: NASA*

Clean Air Tech for Spacecraft Helps Fight Pandemic

Clean air, always a priority in space, gained importance on Earth in slowing virus spread



NASA astronaut Peggy Whitson checks out soybean plants growing in the Advanced Astroculture (ADVASC) plant-growth chamber on the space station in 2002. The photocatalytic air scrubber that regulated ethylene levels in ADVASC and its predecessor turned out to eliminate many other contaminants and eventually led to several lines of commercial air purifiers. Credit: NASA



As engineers at the NASA-funded Wisconsin Center for Space Automation and Robotics built the Astroculture plant-growth chamber in the 1990s, they came up with photocatalytic oxidation as a way to prevent the buildup of ethylene, a plant growth hormone that accelerates ripening and withering. Credit: NASA

Early in the COVID-19 pandemic, as it became clear that the novel coronavirus was transmitted through the air, several companies realized their NASA-derived air-quality technologies could help combat its spread. And they soon found themselves overwhelmed by demand from schools, hospitals, shopping centers, office buildings, airports, and even buses.

One of these was ActivePure Technology, formerly Aerus Holdings (*Spinoff* 2015, 2018). Just after lockdowns took effect in March of 2020, Joe Urso, CEO and chairman of the Dallas-based company, said ActivePure had gone through six months' worth of its inventory in the preceding few weeks.

By that December, Urso said business was steady at about five times pre-pandemic levels.

At TFI Environmental Company Inc., CEO and director John Hurley noted that products like his company's Respicaire air purifiers, which use the same family of technology as ActivePure's, usually fill a small niche – "until something like this happens."

Accustomed to working to convince people of the importance of indoor air quality, in late 2020 he said his Toronto-based company, swamped with orders, no longer had to convince anyone.

Air purifiers made by ActivePure Technologies LLC, based in Dallas, proved able to eliminate the SARS-CoV-2 virus in enclosed spaces, and the company had a model approved for medical use in 2020. The devices use photocatalytic oxidation, pioneered under funding from NASA in the 1990s as a way to improve plant growth in spacecraft.

And by March of 2021, Italian company Airgloss, of Rome, had been out of inventory for months. Airgloss makes air-quality sensors, not purifiers, intended to help HVAC systems and air purifiers improve efficiency and air quality. It soon became apparent, though, that the company's technology could help reduce the risk of COVID-19 transmission.

Airgloss cofounder and CEO Ciro Formisano echoed Hurley's assessment: "Before COVID-19, air quality was something you had to think about, but it was not that interesting to many people. Now people are becoming more and more interested in what's in the air."



ActivePure Technology's Medical Guardian air purifier got Food and Drug Administration clearance as a medical device in June of 2020, as hospitals and other medical facilities were looking for ways to prevent the spread of the novel coronavirus. Credit: ActivePure Technology



Two OXY 4-MB air purifiers from Respicaire are installed in the air handling unit at Synergy Flavors Inc. in Wauconda, Illinois. Credit: Jensen's Plumbing & Heating

Spacecraft: The Ultimate Indoor Environment

Respicaire's most popular products, and all of ActivePure's air purifiers, are based on a technology developed in the 1990s at the Wisconsin Center for Space Automation and Robotics (WCSAR), a NASA Research Partnership Center at the University of Wisconsin-Madison at the time, sponsored by the space agency's Marshall Space Flight Center in Huntsville, Alabama. Researchers there wanted to eliminate the plant hormone ethylene from the air around plants in spacecraft. Without gravity to move the air around, ethylene accumulated around plants, causing premature withering. But the solution they devised, known as photocatalytic oxidation, eliminated a lot more than ethylene.

Photocatalytic oxidation starts when ultraviolet light hits titanium dioxide, a common, naturally occurring chemical compound installed inside the device. This releases electrons, which then combine with oxygen and water molecules in the surrounding air. The oxygen and water, now with a charge, attract organic contaminants, causing reactions that turn them into carbon dioxide and water. Among the pollutants destroyed are volatile organic compounds and other harmful or odor-causing chemicals, as well as mold spores, bacteria, and viruses.

Marc Anderson, the professor who led the project at WCSAR, was one of two researchers leading efforts during the 1980s to purify air and water with titanium dioxide-induced photocatalytic oxidation – the other was Akira Fujishima at the University of Tokyo. While the technology has

The OXY 4 air purifier, based on photocatalytic oxidation, is one of the most popular Respicaire air purifiers. This one incorporates two modules to scale up for a large commercial space. Credit: TFI Environmental Company

gained popularity in the last 20 years, Anderson said, "Fujishima and I were among the earlier scientists refining this photocatalytic process to make it a practical environmental technology. Now they're pretty much all building on work we all did nearly three decades ago."

At TFI Environmental, Hurley said he was surprised when he discovered the technique while scouring air-purification research. "NASA, to me, was rocket engines and fancy technology and all kinds of expensive gear."

However, photocatalytic oxidation wasn't the perfect solution. For example, the process can generate ozone, which can be harmful, and organic compounds might be only partially broken down, resulting in unwanted chemicals. Each company has made advances to mitigate these downsides.

Testing has shown that neither company's devices add ozone to the air. Last summer, the U.S. Food and Drug Administration (FDA) cleared ActivePure's new Medical Guardian product as a medical device on the basis of its efficacy and safety, including assurance that it doesn't cause concerning chemical by-products through partial oxidation. Respicaire devices often incorporate a combination of photocatalytic oxidation and other technology like activated-carbon filters that remove chemicals and particulate matter.



Italian astronaut Roberto Vittori holds up the Italian Electronic Nose for Space Exploration (IENOS) experiment aboard the space station, where he tested the technology in 2011 with help from NASA. *Credit: NASA*

TFI Environmental Inc. of Toronto based several of its Respire air purifiers on NASA-funded research into the use of photocatalytic oxidation to scrub the air in a spaceborne plant-growth chamber. TFI's devices proved able to kill the novel coronavirus and found widespread demand during the pandemic.

ActivePure now incorporates photocatalytic oxidation into about 100 different air purifiers under several brand names, from portable units to those that fit in air ducts, cars, or elevators.

'Electronic Nose' Smells Trouble

Airgloss CEO Formisano originally helped create his company's technology, an "electronic nose," working with a university in Rome, but the technology got a boost when the Italian Space Agency selected it for testing, with NASA's help, on a U.S. module of the International Space Station.

It uses a series of oscillating quartz microbalances – scales that sense tiny weight variations – coated with different polymer films and coupled with artificial intelligence software. The polymers react to different substances in the air, causing slight changes in the microbalances' oscillation frequencies. Together, these changes in frequency let the pattern-recognition software identify and quantify substances in the air.



Three of the IENOS devices were delivered in a single package to the space station in 2011. The IENOS inventors have now commercialized the technology through the Italian company Airgloss. *Credit: NASA*

Marshall scientist Jay Perry, who has worked with photocatalytic oxidation as the center's senior engineer for life-support systems and space station air quality, emphasized that such combinations of technology are advisable.

"Photocatalytic oxidation and ionizing technologies are not standalone indoor air-quality solutions and must be part of a well-designed and -maintained HVAC system that includes highly effective filters to achieve good indoor air quality," Perry said.

Testing last year showed that both companies' purifiers were effective in eliminating the SARS-CoV-2 virus.

Respire's products, including the popular OXY 4 air purifiers, are all designed to fit into the ducts of heating and cooling systems, where multiple units can be stacked to purify the air in larger commercial spaces, Hurley said.

After NASA and the Italian Space Agency sent an "electronic nose" for testing on the space station, its inventors founded Airgloss SRL in Rome and incorporated the technology into an air-quality sensor, which can also calculate the risk of COVID-19 spread in an indoor space.

"It fell within the general interest of NASA for technology to detect contaminants aboard the space station," said Francesco Santoro of Italy's Aerospace Logistics Technology Engineering Company (ALTEC), a public-private company co-owned by the country's space agency. Santoro, then the ALTEC team leader for the Italian Space Agency office at NASA's Kennedy Space Center in Florida, helped prepare the experiment to fly to the station in 2011.

NASA helped sponsor the experiment, known as the Italian Electronic Nose for Space Exploration, which flew on space shuttle mission STS-134.



Airgloss' air-quality sensors work in conjunction with a thermostat to regulate ventilation and manage indoor air, sending alerts and reports. During the pandemic, the company learned how the sensors could calculate a space's risk of COVID-19 spread. *Credit: Airgloss*

Formisano said developing a product for space taught the company how to build and rigorously test robust sensors. "Without NASA, Airgloss wouldn't exist."

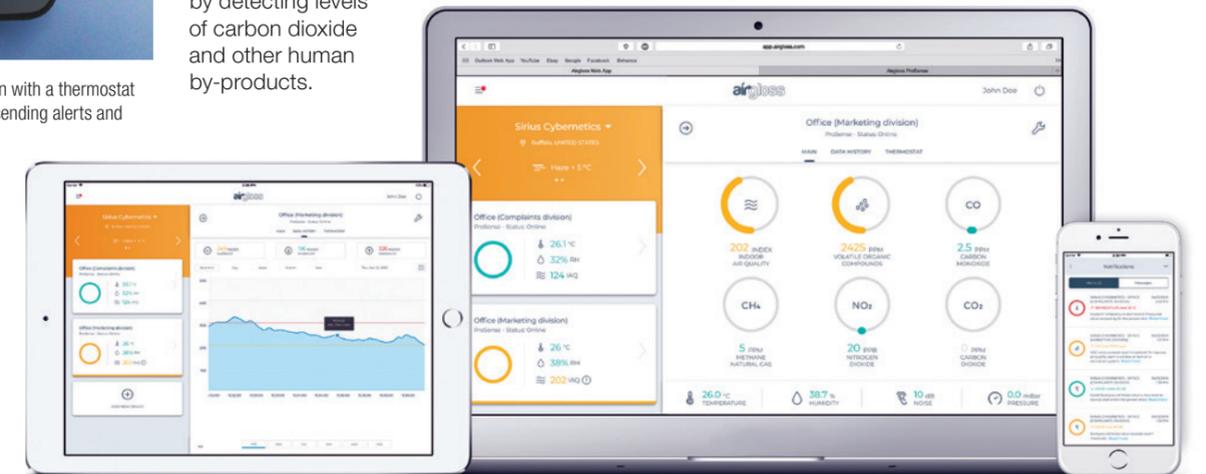
The testing showed promise, and in 2014, Formisano and colleague Maryna Lotsman founded Airgloss to commercialize the technology. The company's first standalone product, ProSense, designed for commercial, public, or office space, was released in 2018, followed by the more home-oriented Comfort Kit in 2021.

The devices monitor volatile organic compounds and dangerous gases as well as humidity and even ambient noise and lighting. Working together with a thermostat, and possibly an air purifier, they automate a building's entire air-management system. They also use WiFi to alert users to issues with the indoor environment and deliver regular reports and tips to improve it.

Airgloss is also working with original equipment manufacturers to integrate its sensors into appliances, such as a range hood that starts up automatically when it senses cooking odors, and even automobile ventilation systems. And in light of the pandemic, the company started working with manufacturers to automate air purifiers.

Sniffing Out Virus Risks

In one pilot program, the company partnered with energy-efficiency-as-a-service company Minimise to automate climate control in a Florida school district. The program happened to coincide with school reopening plans, and organizers realized Airgloss technology could sense room occupancy by detecting levels of carbon dioxide and other human by-products.



Airgloss sensors measure volatile organic compounds, carbon monoxide, carbon dioxide, nitrogen dioxide, methane, humidity, and even ambient noise and lighting to generate detailed reports that they deliver to devices via WiFi. *Credit: Airgloss*

As a room becomes more crowded, the HVAC system can inject more fresh air, diluting expelled breath, and it can turn on air purifiers or suggest other actions.

This led to a display panel that other customers now use to show the "virus propagation risk index" in shared spaces, Formisano said. The information lets people know to reduce crowding or take other steps. "People are becoming aware that they have to contribute to COVID-19 mitigation."

These and other projects ensure that interest in Airgloss technology will continue after concerns about the novel coronavirus subside.

A fume extraction company is experimenting with the sensors for detecting residual pollutants in workplaces. Other pilot projects successfully tried out the technology to determine the purity and quality of petroleum, to let drones analyze pesticides on crops, and to detect food deterioration inside refrigerators. A partnership with the European Institute of Oncology in Milan determined that the sensors had a more than 85% success rate in detecting early-stage lung cancer, although Formisano said the company has yet to begin the lengthy certification process for medical applications.

Meanwhile, he said, customers are looking for help from products they trust. "And people trust us because our technology has been proven through space station testing."

Santoro agreed: "This is a shining example of how space-tested technology can have follow-on applications on Earth." ●

'Reflecting' on Life's Daily Challenges

Fabric spun off from reflective space insulation lines lightweight rain jackets

Hema Nambiar wants you to ask why her start-up company is called 13-One. There's a story behind the name, one that culminates with Nambiar and more than 5,000 other women massed in New York's Central Park, heads bobbing on a shimmering sea of reflective "space blankets."

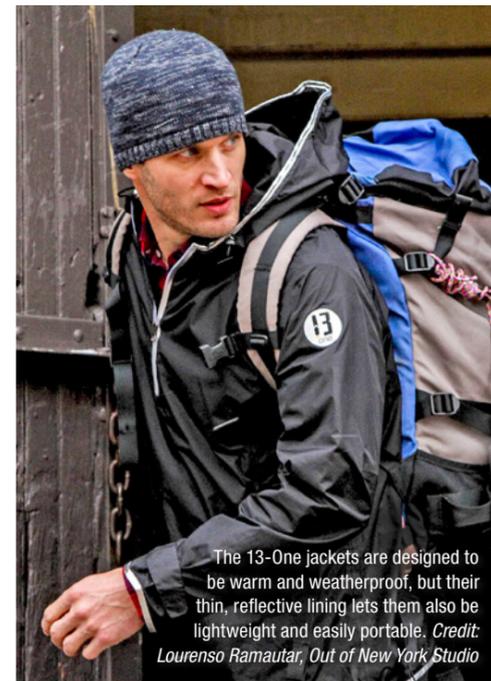
Inspired by the "space blankets" at her first post-surgery race, a runner founded 13-One in Larchmont, New York, to turn a fabric based on NASA's radiant barrier insulation into a line of warm, portable, weatherproof jackets.

They were on the triumphant side of the finish line of a 2011 women's half-marathon, having completed the 13.1-mile circuit that would inspire her company's name.

For Nambiar, those 13.1 miles were only the latest steps in a much longer journey. Four years earlier, she'd suffered a life-threatening internal injury. It resurfaced in 2009, requiring a second massive surgery. After another long recovery period, her doctor finally gave her permission to run no more than a half-marathon. So she did.

Afterward, in the glow of victory, life's other challenges also seemed manageable, she said. "And I thought, 'Every day is a marathon, whether you're running or just taking care of your kids.'" She wanted to hang on to the moment, and her attention turned to the gleam of the thin, mirrored blankets she and her fellow runners now clutched around themselves.

Space blankets, so named for their NASA origin, are based on radiant barrier technology. In the mid-1960s, as NASA geared up for its Moon shot, the agency's Marshall Space Flight Center in Huntsville, Alabama, commissioned a "superinsulation" that would become the model for insulating NASA's spacesuits, spacecraft, and cryogenic tanks. The material comprised several layers of thin, durable plastic, each coated with a vacuum-deposited metal film and crinkled to create



The 13-One jackets are designed to be warm and weatherproof, but their thin, reflective lining lets them also be lightweight and easily portable. Credit: Lourenso Ramautar, Out of New York Studio

13-One founder Hema Nambiar sports a "space blanket" after finishing a half-marathon in 2011. The experience, as she was recovering from a life-threatening injury and subsequent surgeries, inspired her to incorporate a fabric based on this NASA invention into a line of jackets designed for marathon day or any day. Credit: Anant Nambiar



In May 2009, astronaut John Grunsfeld works on repairs to the Hubble Space Telescope, including replacing three thermal blankets protecting the telescope's electronics. This multi-layer reflective thin-film insulation, also known as radiant barrier, manages temperatures in almost all NASA spacecraft and spacesuits and is also one of the agency's most ubiquitous spinoffs, appearing in countless products, including new lightweight jackets from 13-One. Credit: NASA

gaps between the layers. While the shiny films reflected radiated heat, the gaps between them prevented heat conduction, creating an insulation that was thin, lightweight, and extremely effective.

As one of NASA's most ubiquitous spinoffs, it can be found hidden inside the walls and roofs of buildings, in cryogenic tanks and MRI machines, in winter gear, and in cases for electronic devices, among other applications. (Nearly half the issues of *Spinoff* since 1976 have featured products using radiant barrier technology.) When a longtime supplier of the insulation for NASA shut down in the early 1980s, one of its former employees founded Advanced Flexible Materials Inc. and created the Heatsheets brand, marketing products like the space blankets now traditionally distributed after races to prevent a dangerous drop in body temperature (*Spinoff* 2006, 2010, 2018).

Nambiar contacted Heatsheets and learned the company was marketing a fabric called Ultraflect based on the technology. She obtained a sample and the rights to use it in a jacket, and she drew up designs. Following a 2016 Kickstarter campaign, 13-One of Larchmont, New York, was in business.

The resulting line of jackets have a black exterior with an Ultraflect lining to reflect body heat. They're warm while weighing less than a pound and wind- and water-resistant, and they easily pack into a small, built-in pouch.

The company's client base continues to grow each year, with customers across North America, Europe, and Australia, but Nambiar said nothing is as gratifying as the feedback she gets from them, with users testifying to their jackets' performance through everything from long runs and rainy soccer games to coastal drives with the top down.

A mother of three who's back in the stands in all kinds of weather at her now-grown children's baseball and soccer games, Nambiar said she hopes the jackets help others like her to get through the day and remember that each one is a marathon. ●

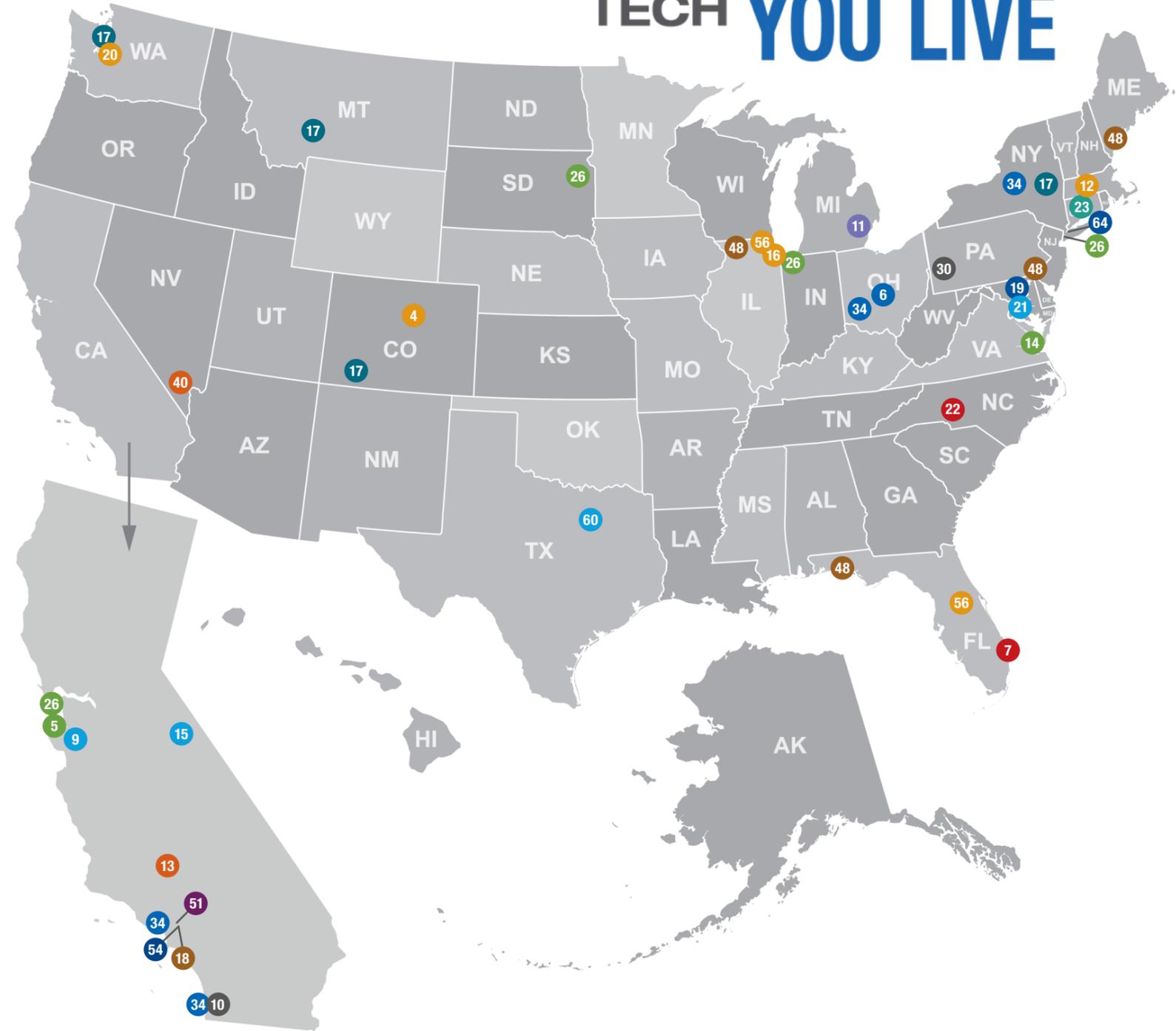
The secret to 13-One's warm, lightweight jackets is in their lining. Ultraflect fabric is based on NASA's invention of radiant barrier insulation and is made by Advanced Flexible Materials, which was founded by a former employee of a longtime supplier of insulation for NASA. Credit: Lourenso Ramautar, Out of New York Studio



Spinoff Technology Across the Nation

Page	Article	Technology	Company, Location
4	Measuring Moon Dust to Fight Air Pollution	Air-quality sensor system	Lunar Outpost, Denver, CO
5	Microbes Help Trees Clean Up Pollution	Plant endophytes for environmental cleanup	Intrinsyx Environmental, Moffett Field, CA
6	Pounding Metal Parts into Profit	Ultrasonic additive manufacturing	Fabrisonic, Columbus, OH
7	Water Purification Anywhere on Earth	Filter medium for water bottles	nkd LIFE, West Palm Beach, FL
9	Plasma Improves 3D Electronics Printing	Plasma jet 3D electronics printer	Space Foundry, San Jose, CA
10	Computers Tough Enough For Space	Processor for cubesats	Space Micro, San Diego, CA
11	Software Keeps Cloud Traffic Moving	Portable batch system for computer workloads	Altair Engineering, Troy, MI
12	Antennas Find Their Cool	Ultra-thin polymer aerogel	Blueshift Materials, Spencer, MA
13	Test Rockets Prepare for Distant Landings	Rocket-powered vertical takeoff and landing	Masten Space Systems, Mojave, CA
14	Swinging the HAMR	Hybrid remotely piloted aircraft	Advanced Aircraft Company, Hampton, VA
15	Getting Water Out of Snow with NASA Tech	Lidar and spectrometer sensors, modeling software	Airborne Snow Observatories, Mammoth Lakes, CA
16	Stay Safe with Battery Testing for Space	Battery testing methods	Underwriters Laboratories, Northbrook, IL
17	Keeping Warmer in the Great Outdoors	Outdoor gear with new spin on aerogel insulation	Cold Case Gear, Pagosa Springs, CO
			Outdoor Research, Seattle, WA
			PrimaLoft, Latham, NY
			SITKA Gear, Bozeman, MN
18	The 'Cobot' Revolution Is Coming	Bulk metallic glass for robot gears, more	Amorphology, Pasadena, CA
19	Satellite Software Helps Global Forecasting	Satellite scheduling software	Orbit Logic, Greenbelt, MD
20	From a Lightbox to Lamps	LED lighting for maintaining circadian rhythms	Ario, Seattle, WA
21	'Positive Energy' Captures Contaminants	Water filtration medium	Western Water International, Forestville, MD
22	From Spacesuits to Racing Suits	Phase-change materials	Walero, Mooresville, NC
23	Some Engineering Is Only Skin Deep	Surface finishing for 3D-printed superalloys	REM Surface Engineering, Southington, CT
26	A Moveable Feast: Plant Research for Space Advances Earth Agriculture	Growing techniques and research data for controlled environment agriculture	Plenty Unlimited, San Francisco, CA
			Green Sense Farm Holdings, Portage, IN
			Bowery Farming, New York, NY
			CSS Farms, Watertown, SD
30	NASA Helps Private Lander Shoot for the Moon	Commercial lunar lander	Astrobotic Technology, Pittsburgh, PA
34	NASA Helps Drones Take Flight	Drone traffic management app	Avison, Santa Monica, CA
		Detect-and-avoid system for aircraft	General Atomics, San Diego, CA
		Drone flight testing environment	CAL Analytics, Beavercreek, OH
40	Space Pens, Pencils, and How NASA Takes Notes in Space	Space Pen for writing under adverse conditions	Fisher Pen Company, Boulder City, NV
		Forecasting Saharan Dust to Minimize Health Risks	University of Puerto Rico, San Juan, Puerto Rico
44	NASA's Robotic Glove Finds Commercial Handhold	Ironhand industrial grip-enhancing robotic glove	Bioservo Technologies, Stockholm, Sweden
48	Safely Detoxifying Soil and Groundwater with NASA Technology	Emulsified zero-valent iron (EZVI)	Provectus, Freeport, IL
			Toxicological and Environmental Associates, Miramar Beach, FL
			Woodard & Curran, Portland, ME
			Terra Systems, Claymont, DE
51	Expertise Flows from Computer Cognition	Expert system AI technology	Beyond Limits, Glendale, CA
54	Lasers Make Waves in Self-Driving Cars, Quantum Devices	Optoelectronic oscillator and optical resonator	OEwaves, Pasadena, CA
56	Lighting in a Bottle	Circadian rhythm and ultraviolet LED lighting	Healthe, Orlando, FL
		LED-based grow lights	VividGro, Chicago, IL
60	Clean Air Tech for Spacecraft Helps Fight Pandemic	Air purifiers based on photocatalytic oxidation	ActivePure Technology, Dallas, TX
		Air-quality sensor to manage indoor environments	TFI Environmental, Toronto, Canada
64	'Reflecting' on Life's Daily Challenges	Jackets with Ultraflect lining	Airgloss, Rome, Italy
			13-One, Larchmont, NY

NASA SPACE TECH WHERE YOU LIVE



The seven-member Expedition 64 crew gathers together on New Year's Day 2021 for a portrait inside the International Space Station's "window to the world," the cupola. Clockwise from top are Roscosmos cosmonaut Sergey Kud-Sverchkov; NASA astronauts Kate Rubins, Victor Glover, and Michael Hopkins; Roscosmos cosmonaut and station commander Sergey Ryzhikov; JAXA astronaut Soichi Noguchi; and NASA astronaut Shannon Walker.

Technology Transfer Program

NASA's inventors are constantly innovating to meet the needs of our many missions – and the Technology Transfer program works tirelessly behind the scenes to ensure the technology finds the widest possible usage beyond the agency. This section showcases a few of the new ways the program is helping NASA technology find a home, and make an impact, here on Earth.

Improving the Ways NASA Brings Technology Down to Earth

As the pandemic forced the nation to shut down in early 2020, engineers at NASA's Jet Propulsion Laboratory in Southern California shifted focus from their mission work to the COVID-19 fight. Developed in just 37 days, VITAL (short for Ventilator Intervention Technology Accessible Locally) was created specifically to help COVID-19 patients.

NASA's ventilator is going far beyond California to help the fight. In India, several companies are already manufacturing VITAL. They are among 27 companies in 16 countries that have licensed the technology after JPL received over 100 license applications. Several of these companies, including one in the United States, are now ramping up production to help healthcare systems overwhelmed by increasing new infections.



After testing a ventilator prototype developed by NASA's Jet Propulsion Laboratory, doctors in the Department of Anesthesiology and the Human Simulation Lab at the Icahn School of Medicine at Mount Sinai in New York City give a thumbs-up. *Credit: NASA*

A Better Way to Transfer

While VITAL is one of the most-licensed NASA technologies of all time, its success only makes up a small fraction of the technologies licensed to industry each year.

In 2020 alone, the agency executed 173 licenses – a record-breaking number since 1958, the very beginning of NASA. The NASA Technology Transfer (T2) program also had an incredible year executing software usage agreements, with over 4,500 agreements released.

A significant contributor to this success is NASA's dedication to automating, streamlining, and improving the licensing and software release processes. Licensees can search and request all available technologies through T2's website (technology.nasa.gov), eliminating tedious paperwork.

The software release process also received a complete overhaul. Due to the rigorous security vetting required for new users, download packages once took weeks to receive via email. Now, users can receive their software in as little as a day from software.nasa.gov, the digital catalog full of thousands of codes created originally for remote sensing satellites, shuttle launches, and even the Mars rovers Curiosity and Perseverance.

This dedication to improving technology transfer, and therefore all that it contributes to society, doesn't stop at process improvements. NASA is also finding new ways to engage a community that makes the new products and services born from space-exploration technologies possible – entrepreneurs.

Cultivating the Next Generation of Entrepreneurs

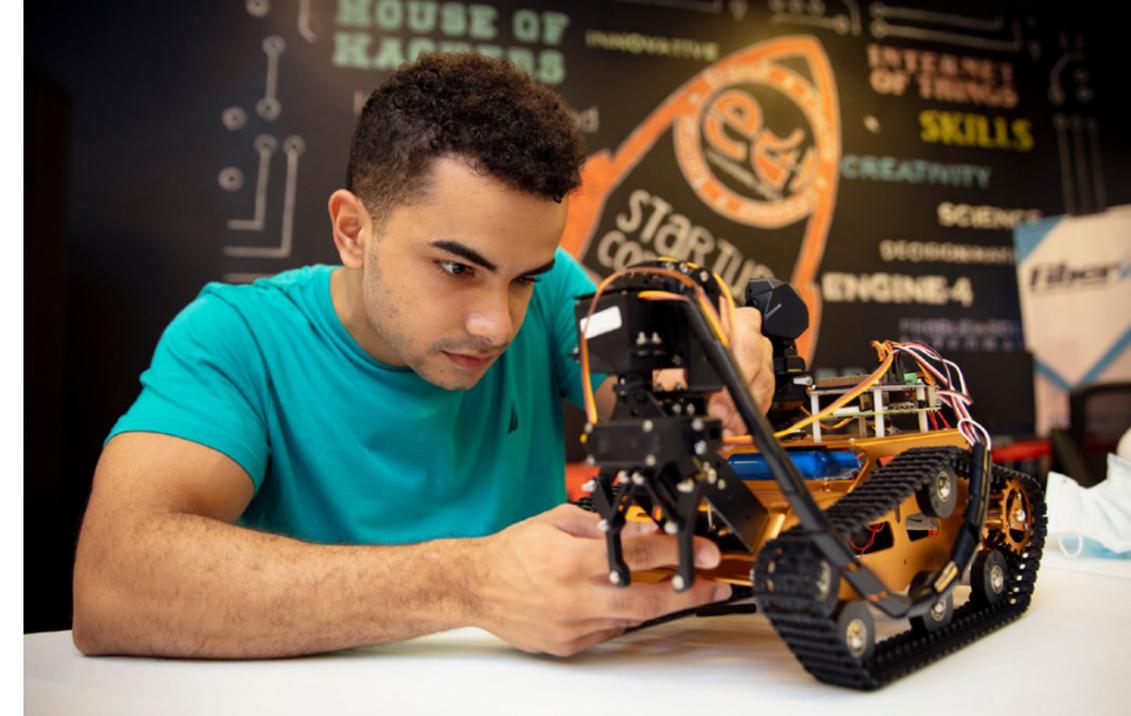
This past year, the program ramped up several initiatives to help cultivate the next generation of entrepreneurs – here at NASA, in schools, and across the nation – who will help shepherd technology from design to products on shelves.

One such program is the Technology Transfer Expansion (T2X) NASA Entrepreneurial Workforce initiative, which is designed specifically for NASA researchers. Many of the cutting-edge technologies our engineers and scientists develop for critical mission and program needs have other applications beyond space exploration. However, expertise in engineering doesn't always translate to entrepreneurship.

This program trains NASA's workforce to think like entrepreneurs so they can better see the commercial potential in their areas of expertise. This new skill allows innovators to interact with commercial partners interested in licensing their technologies, increasing the chances of a successful new product or service available to the public.

Armed with these new skills, NASA innovators can then market their technologies directly to industry through a series of webinars hosted by T2. Inventor webinars have already attracted more than 6,400 registrants, leading to dozens of new licenses.

But this type of training and outreach doesn't stop with the NASA inventors. In 2021, T2 collaborated with:



A student from the 2021 Challenge to Innovate: NASA Edition works on a rover prototype that uses NASA technology to help farmers harvest fruits and vegetables. *Credit: Puerto Rico Science, Technology, and Research Trust (PRSTR) and Parallel 18.*

- **U.S. Department of Commerce's Minority Business Development Agency (MBDA).** In 2021 alone, more than 200 minority entrepreneurs learned about available resources to help launch businesses, such as technologies available for licensing in the fields of robotics, human health, and more through a series of virtual events.
- **Tech Center Research Park Accelerator Network Program (TCRP ANP).** NASA's partnership with TCRP ANP aims to accelerate technology commercialization through entrepreneurship programming and strategic business growth services. TCRP ANP reaches traditionally underrepresented entrepreneurs and works to identify global applications for federally funded technologies like NASA's.
- **FedTech Startup Studio.** NASA's continued partnership with FedTech enabled the launch of four NASA technology-derived start-ups that created products and services to solve problems here on Earth. The FedTech Startup Studio pairs entrepreneurs with federal lab technologies to launch ventures.

- **Puerto Rico Science, Technology, and Research Trust (PRSTR).** Run by Parallel 18, an organization created by PRSTR, the 12-week Challenge to Innovate: NASA Edition included roughly 60 science, technology, engineering,

and mathematics (STEM) college students from across Puerto Rico. They developed business concepts around six NASA technologies licensed by PRSTR and demonstrated their physical prototypes in two industry sectors: agriculture and pharmaceuticals. Parallel 18 presented first-place winners for each industry sector \$2,000 to continue development, and second-place winners won \$1,500.

NASA is also increasing its reach in the classroom by expanding the Technology Transfer University (T2U) program. Under this initiative, student entrepreneurs build case studies with NASA's patent portfolio while learning about best practices for commercialization, available software, and the licensing process. This year the list of active T2U partnerships almost doubled, to 32 universities, including seven minority-serving institutions, across 15 states – and the list keeps growing.

Back down to Earth

By launching new activities to promote entrepreneurial spirit and teach valuable skills for building businesses, NASA is not only fostering an atmosphere of inclusion, it's building up future business leaders who can create products and services to enhance the economy, promote job growth, solve global problems, and even save lives. That is why bringing NASA technology down to Earth is a mission worth doing – and doing well. ●



Entrepreneurs attending the Tech Center Research Park Accelerator Network event in 2021 learn about NASA technologies and ways to use them to solve business problems. *Credit: NASA*

Will the next spinoff be yours?

Our technology is ready for you at technology.nasa.gov

Our portfolio includes:

- More than 1,200 patented technologies
- Hundreds of innovations now in the public domain
- More than 700 software codes

Whether you're looking to start a new company using NASA technology, enhance an existing product, or create a new product line, you can gain a competitive edge in the marketplace by putting NASA technology to work for you.



**NASA TECHNOLOGY
TRANSFER PROGRAM**

BRINGING NASA TECHNOLOGY DOWN TO EARTH

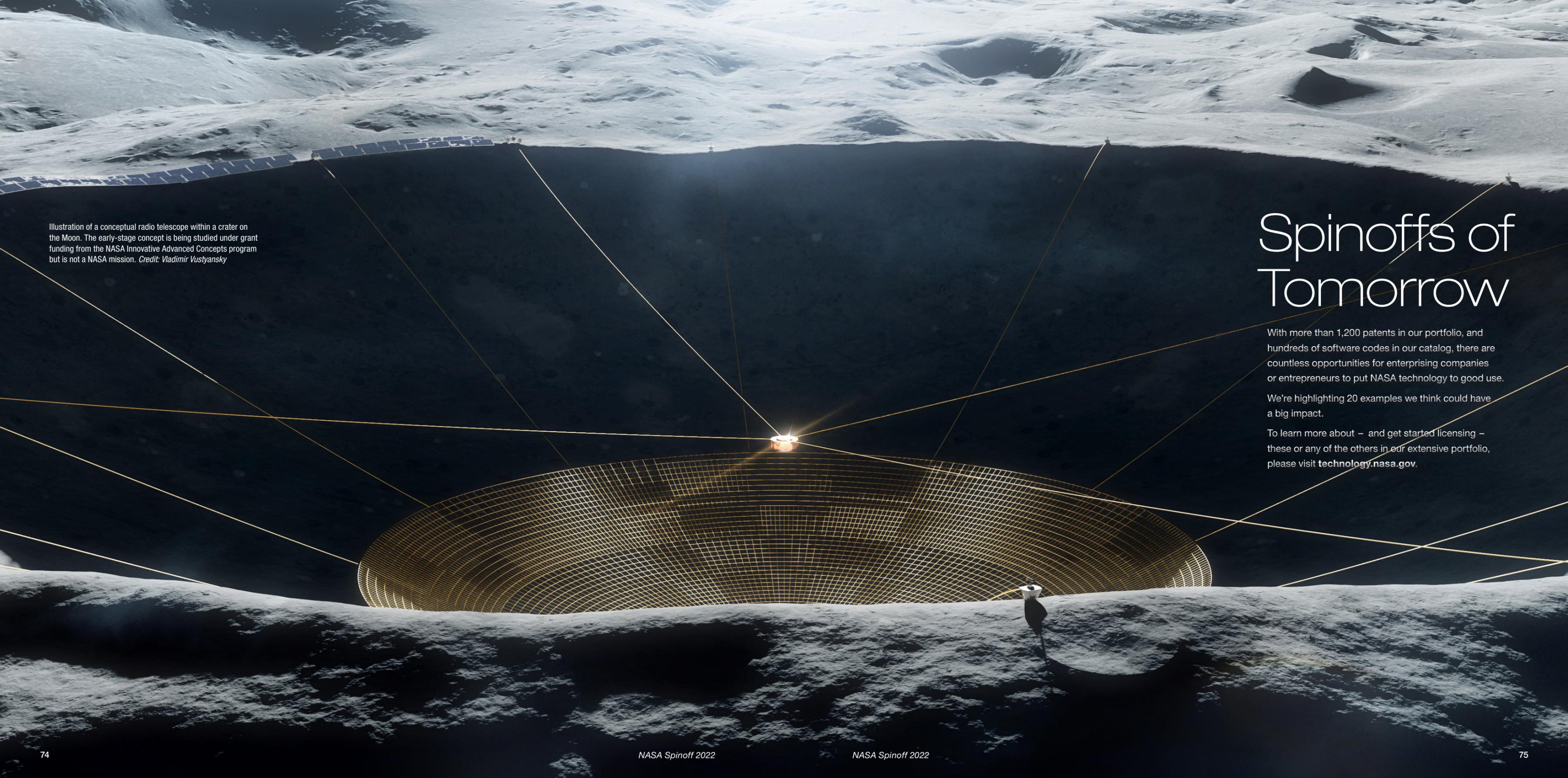


Illustration of a conceptual radio telescope within a crater on the Moon. The early-stage concept is being studied under grant funding from the NASA Innovative Advanced Concepts program but is not a NASA mission. *Credit: Vladimir Vustyansky*

Spinoffs of Tomorrow

With more than 1,200 patents in our portfolio, and hundreds of software codes in our catalog, there are countless opportunities for enterprising companies or entrepreneurs to put NASA technology to good use.

We're highlighting 20 examples we think could have a big impact.

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

Ames

Convert carbon dioxide to fuel with the power of the Sun

A low-cost nanomaterial thin-film device

Engineers at Ames Research Center have developed a new technology that can convert the greenhouse gas carbon dioxide (CO₂) into fuel before it is emitted into the atmosphere – helping mitigate the effects of burning fossil fuels.

Metal oxide thin films are used to create a photoelectrochemical cell that is powered by solar energy. The device can be used to capture carbon dioxide produced in industrial processes and deployed to the commercial market with low manufacturing and materials costs.

More importantly, it results in a zero-carbon footprint, with the Sun powering a compact device that recycles CO₂ into fuels compatible with all existing fuel utilities.



Benefits

- Efficiently reduces carbon dioxide emissions
- Produces useful fuels
- Operates inexpensively
- Uses solar energy as the only power source

Applications

- Carbon capture technologies
- Photoelectrochemistry
- Automobile industry
- Materials science

Armstrong

Fiber-Optic Sensing Technologies

Dramatic improvements for structural health monitoring and tank gauging applications

Advanced sensors and innovative algorithms combine in this patented, award-winning package to accurately and cost-effectively monitor multiple critical parameters of storage tanks simultaneously and in real time.

Known as FOSS (for fiber-optic sensing system), the technologies can monitor the tank's structure as well as its inventory, including amounts, temperatures, and stratification (oil vs. water, sediment vs. liquid, thermal layers).



Benefits

- Provides unparalleled capabilities at a drastically reduced cost
- Low power with ultra-efficient algorithms and high-speed processing platform
- Automatically increases resolution where and when needed
- Operates effectively in humid – or even liquid – environments and withstands cryogenic temperatures and mechanical vibrations

Applications

- Structural health and integrity
- Tank gauging
- Safety and protection
- Medical uses



Benefits

- Accurate and precise
- Portable to mobile platforms
- Highly secure, high universality

Applications

- Mobile biometrics
- Banks and financial institutions
- Healthcare biometrics
- E-commerce and web applications
- Homeland security, airports, national ID documents

Unlock Devices with Unique Heartbeats

HeartBeatID

Forget complicated and easy-to-hack passwords: modern devices protect privacy by requiring a unique biometric feature, like a fingerprint, to unlock or authenticate a user. And now NASA has invented a next-generation system for biometric identity verification – using heartbeats.

Engineers at Ames Research Center have devised a method and associated system for authenticating or declining to authenticate an identity by at least 192 statistical parameters for electrical signals associated with heart waves.

It can be used in everything from replacing an individual's computer passwords to accessing a bank account.

Lower the Boom

Pilots can reduce noise pollution by placing sonic booms away from populated areas

One barrier to widespread adoption of supersonic aircraft is the window-rattling boom that occurs when the plane surpasses the speed of sound.

The supersonic shock wave forms a cone of pressurized air molecules that propagates outward in all directions and extends to the ground. Factors that influence sonic booms include aircraft weight, size, and shape, in addition to its altitude, speed, acceleration, and flight path, as well as weather or atmospheric conditions.

NASA's Real-Time Sonic Boom Display takes all these factors into account and enables pilots to place loud booms in specific locations away from populated areas or prevent them from occurring.

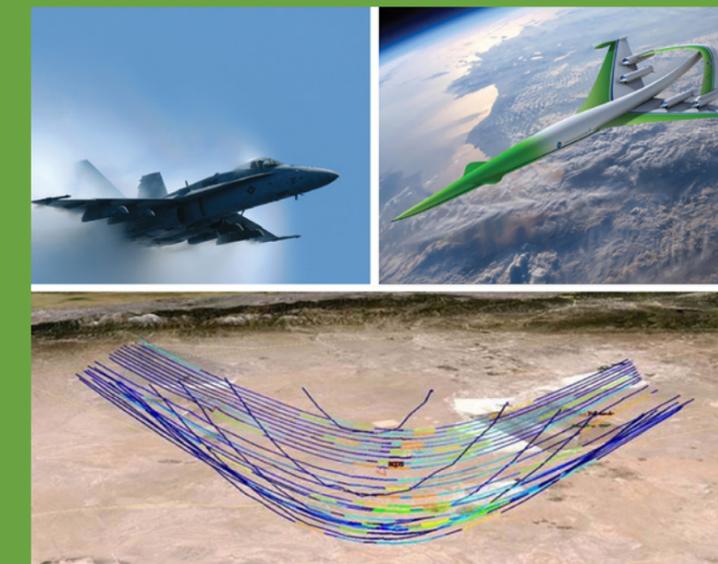
The technology can be used on current-generation supersonic aircraft, which generate loud sonic booms, as well as future-generation low-boom aircraft, anticipated to be quiet enough to be flown over land.

Benefits

- Works in cockpits and flight control rooms
- Reduces noise pollution
- Provides information in real time

Applications

- Commercial supersonic vehicle design
- Federal Aviation Administration regulatory compliance
- Aeronautics research, development, simulation, and testing



Temperature-Sensitive Coating Enables High-Heat Measurement

A low-cost and versatile alternative to photoluminescence techniques

Innovators at Glenn Research Center have developed a temperature-sensitive coating based on hematite (iron III oxide). Painted onto a surface, the coating gradually changes color from a reddish brown at room temperature to black-gray at 1,100 degrees Fahrenheit. The color change is reversible and repeatable, as temperature cycles from low to high and back again.

Because Glenn's innovation works in white light, which is easily produced, color changes can be detected and recorded using low-cost sensors.

The coating is inexpensive and easy to apply, and it contours to complex surfaces. Developed for use in NASA's high-speed aircraft test facilities, the coating also offers exciting new industrial and automotive potential.



Benefits

- Accurate temperature measurements
- Operating range of 75 to 1,100 degrees Fahrenheit
- Allows for low-cost, white-light illumination
- Can be applied to complex shapes at a specific point or over an entire surface

Applications

- Aerospace (high-speed aircraft flight testing, engine and exhaust measurements, inflatable reentry vehicles)
- Automotive exhaust and engine thermal measurements
- Industrial and residential ovens and furnaces
- Annealing and heat treatment systems for metals
- Heating systems (including space heater safety)

Lotus Coating

Mitigating dust accumulation and repelling liquids

Keeping out the dust that accumulates on the Moon, comets, and other planets is no half-hearted chore. The dust can be abrasive and damaging, both for astronauts breathing it in and the sensitive electronics they and robotic explorers rely on.

Goddard Space Flight Center has developed a unique formulation of a lotus leaf-like nano-textured dust mitigation coating that is durable and transparent and can be applied to a variety of rigid and flexible surfaces. It can be brushed or sprayed on or applied through spin coating.

The coating also has super-hydrophobic properties and can prevent a variety of particles, liquids, or ice from sticking to the coated surface. It can be used for space and aeronautical applications, as well as ground applications.



Benefits

- Works in air, as well as vacuum systems
- Able to coat virtually any surface
- Ideal for surfaces that cannot be easily cleaned
- Easy to formulate and apply

Applications

- Spacecraft surfaces like radiators, mirrors, and solar arrays
- Textile, automotive, health, pharmaceutical, electronics, aeronautics industries
- Cleanroom surfaces, building and construction industry, solar arrays, etc.

Autonomic and Apoptotic Highly Distributed System

Adapts autonomic and apoptotic functions developed for space-to-cloud, grid, and other distributed systems

As computer-based systems become ever more highly distributed, such as via cloud and grid computing, it will become increasingly critical they have autonomic capabilities to self-manage.

Goddard Space Flight Center has developed software that mimics autonomic mechanisms of biological systems, such as the apoptotic process that shuts down cells when they no longer serve a purpose.

The software provides self-management and security for a distributed system such as a satellite swarm in which craft communicate and collaborate. Originally developed for space missions, this capability has now been extended for use in terrestrial applications involving cloud- and grid-based systems and other applications requiring highly distributed operation.

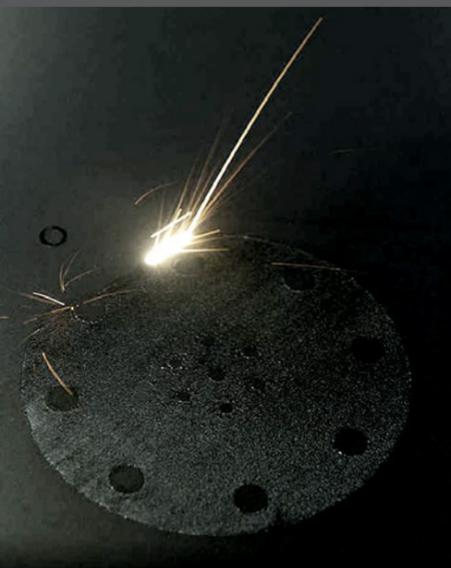


Benefits

- Greater autonomy of distributed computer systems
- Quicker and more robust automatic response to security threats

Applications

- Computer security
- Space exploration
- Commercial satellite systems involving multiple craft working together



Benefits

- Retains mechanical properties at high temperatures
- Can be 3D-printed by a regular SLS machine
- Composites using RTM370 are 30% lighter than metallic parts
- Production process is solvent-free
- RTM370 composites demonstrate high impact resistance and outstanding abrasion resistance

Applications

- Aerospace and automotive manufacturing
- Oil and gas industry
- Construction
- Industrial machinery

3D-Printed Composites for High-Temperature Uses, Including Aerospace

Using laser sintering to manufacture thermoset polyimide composites

Additive manufacturing is a promising new technique to create complex parts more efficiently and economically – but demanding applications like aerospace require high-performance materials and techniques.

Innovators at Glenn Research Center, in collaboration with the University of Louisville and the U.S. Air Force, have developed an additive manufacturing system to produce composite parts that can withstand temperatures above 570 degrees Fahrenheit. The process uses selective laser sintering (SLS) to melt-process a powdered version of NASA's novel RTM370 imide resin filled with finely milled carbon fibers.

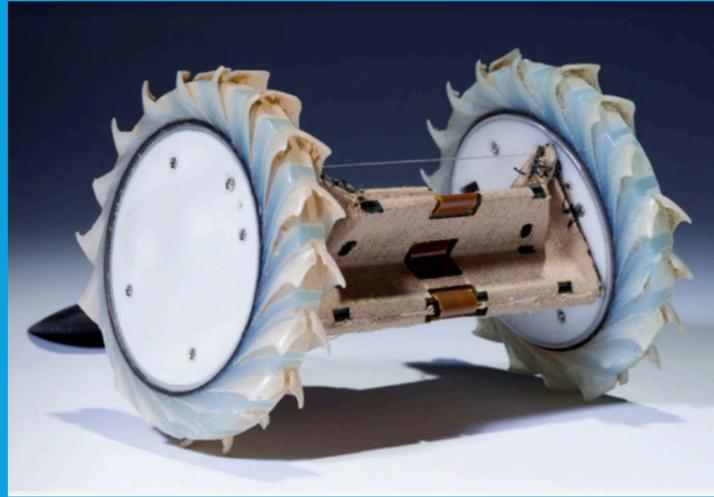
This invention will enable aerospace companies to produce parts with complex geometry for engine components facing high temperatures. It also has a wealth of other potential applications, including printing legacy parts for military aircraft and producing components for high-performance electric cars.

A-PUFFER

A foldable robot that can access tight spaces

Inspired by origami, the foldable Autonomous Pop-Up Flat Folding Explorer Robot (A-PUFFER) was developed to scout regions on the Moon or Mars to gain information about locations that may be difficult or dangerous for astronauts to investigate on foot, such as hard-to-reach craters and narrow caves.

A-PUFFER could be useful in similar circumstances on Earth, scouting in caves and crevices for rescue operations or when environmental conditions are unsafe for human operators.



Benefits

- Autonomously traverses challenging terrain
- Self-optimizes power, data storage
- Multi-agent autonomy enables multiple A-PUFFERs to operate in ways that are not possible with a single rover

Applications

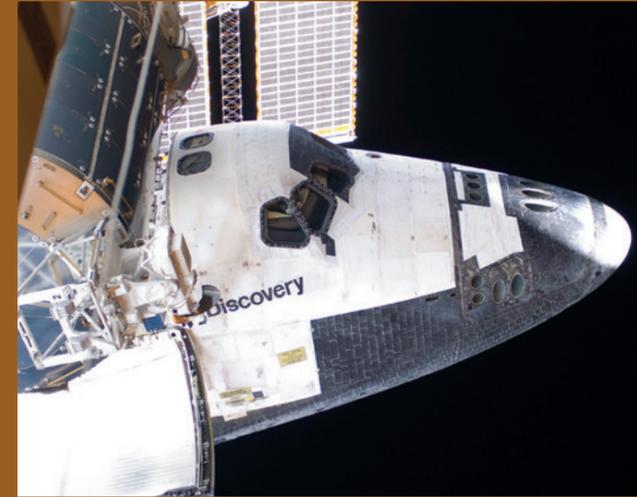
- Scouting wreckage in rescue operations
- Oil and gas exploration

Improved Infrared Contrast Analysis and Imaging

Analysis tool for non-destructive evaluation of composites

Researchers at Johnson Space Center have developed new techniques to analyze flash infrared thermography data, providing efficient and cost-effective enhancements to non-destructive evaluation (NDE) of structures. This improvement offers accuracy not currently available for NDE of composite materials.

Compatible with commercial infrared thermography products, this suite of tools provides both quantitative and qualitative data analysis capabilities and reliable detection of potential issues in composite structures.



Benefits

- Compatible with existing flash thermography hardware systems
- Extracts and constructs images quickly and easily
- Improves flaw detection sensitivity

Applications

- Aerospace
- Power generation
- Construction



Benefits

- Reduces maintenance, retrieval, and refitting costs by allowing autonomous vehicles to stay underwater for years at a time
- Renewable source of electrical power for propulsion, communication, and scientific instruments
- Propeller acts as a combination turbine and motor, providing both propulsion and power generation

Applications

- Ocean study
- Earth sciences
- Underwater surveillance

Underwater Vehicle Propulsion and Power Generation

Vehicle generates power with thermally generated buoyancy changes

The Jet Propulsion Laboratory (JPL) has developed an underwater vehicle that uses thermally generated buoyancy changes to generate electricity and recharge batteries, enabling it to remain underwater for years at a time. Like many cutting-edge underwater vehicles, it's propelled by temperature differentials in ocean water. Unlike conventional vehicles, however, JPL's extracts energy from the vehicle's gliding movement by turning a propeller turbine while in motion, recharging the batteries. The propeller can be turned off to reduce drag, and it can be used to drive the vehicle faster than would be possible with thermal gradients alone.

Non-Destructive Evaluation of Structures

Suite of flash thermography technology

Researchers at Johnson Space Center have improved their flash thermography capabilities by adding new methods of non-destructive evaluation (NDE) to their suite of products.

This NDE technology identifies flaws in materials used in airplanes, drones, and buildings. By adding the transient thermography method, which is able to detect flaws on thicker parts faster than other methods, and the lock-in thermography method, which uses a sinusoidal power cycle to provide a better flaw resolution, the flash thermography NDE technology suite has expanded its applicability to other commonly used infrared thermography techniques.



Benefits

- Able to detect anomalies in thicker material
- Reduces weight and logistics associated with system
- Supports standardization of system components

Applications

- Avionics and aerospace
- Data storage networks
- Industrial process control

Kennedy

Repair Cracks and Reverse Fatigue Damage in Structural Metal

Self-healing aluminum metal matrix composite

Innovators at Kennedy Space Center have developed a new metal matrix composite that can repair itself from large fatigue cracks that occur during the service life of structures such as aircraft.

The composite contains both shape memory alloy reinforcements and some low melting-phase components which, when heated, essentially clamp the crack edges back together and flow material into the gap for a high-strength repair. And this method doesn't require complex surface preparation and bonding, which can be difficult and risky to the structure's strength.



Benefits

- Improve safety of a structure by healing fatigue cracking
- Enables crack repair during flight or service to extend the life of structures
- Works where a crack location is difficult to reach or current repair techniques are not applicable

Applications

- Aircraft structural components such as fuselage skin, frames, doors, tanks, wheel wells, and fuel lines
- Spacecraft structural components for longer missions where current repair technologies are not an option
- Repairing cracks in oil-well casings for the oil and gas industry



Benefits

- Prevents issues with over- or under-watering plants
- Can be constructed using commercial off-the-shelf parts
- Can be sized to accommodate a wide variety of plant sizes in both space and Earth environments

Applications

- Commercial indoor farming
- Tool for science, technology, engineering, and mathematics students

Water and Nutrient Delivery for Controlled Agriculture Environments

Passive nutrient delivery system

Reliable seed germination and plant production requires an environment that isn't too wet or too dry. Researchers at Kennedy Space Center have developed the passive nutrient delivery system (PONDS) to improve water and nutrient delivery for plants grown on the International Space Station.

The technology uses an innovative wicking material to link a water and nutrient reservoir to a growth cylinder where seeds are germinated and plants are produced. PONDS improves oxygen transfer to plants by providing consistent delivery of water and nutrients.



Benefits

- Epoxy coatings are inexpensive and easy to apply
- Production of the fluorinated component is simple

Applications

- Aerospace
- Marine
- Automotive
- Wind energy

Langley

Anti-Insect Coating for Vehicles and Structures

Hydrophobic epoxy coating for insect adhesion mitigation

A buildup of bugs can cause bigger problems than eyesores when it comes to machinery. Insect residue, if not periodically removed, can reduce the efficiency of aircraft. To help fix this problem, innovators at Langley Research Center have developed hydrophobic epoxies that act as an anti-insect coating. The strong, durable coating is useful in a variety of applications, such as protecting wind turbine blades from insect residue.

Heat-Retardant Materials Based on Spacecraft Reentry Thermal Protection

Multilayered fire protection system

Sleeping bags, tents, blankets, or curtains – versatility is just one aspect that makes the heat-retardant materials from Langley Research Center a great solution for emergency fire protection.

The flexible, lightweight technology made of multiple layers of thermal blankets is designed to handle external temperatures of up to 2,000 degrees Fahrenheit. Flight tests have clearly demonstrated how these new heat-retardant materials can protect from extreme conditions. This system can help protect equipment, facilities, and people from fires and other high-heat sources.

Benefits

- Lightweight, portable, and flexible
- Can withstand temperatures up to 2,000 degrees Fahrenheit

Applications

- Personal emergency fire shelter
- Insulation for walls
- Protects property such as apartments or cargo



Marshall

Camera Made for High Vibration and Harsh Environments

Ruggedized infrared camera

Researchers at Marshall Space Flight Center have developed a ruggedized infrared camera system for harsh environments. Advanced modifications allow the camera to survive high-vibration environments, such as spacecraft launches, and improve heat removal for operation in a range of harsh conditions including a vacuum.

The camera assembly has been fully tested in extreme conditions including high vibration, shock, vacuum, and temperature cycling. Although designed for space applications, the assembly can work in harsh environments on Earth, too.



Benefits

- Cost-effective
- Small and lightweight
- Enhances a standard infrared camera to function in extreme environments

Applications

- Imaging systems for satellites, autonomous vehicles, and other spacecraft
- Surveillance and thermal analyses of commercial aircraft engines
- Enhanced imaging capabilities for first responders working in fog, rain, and smoke

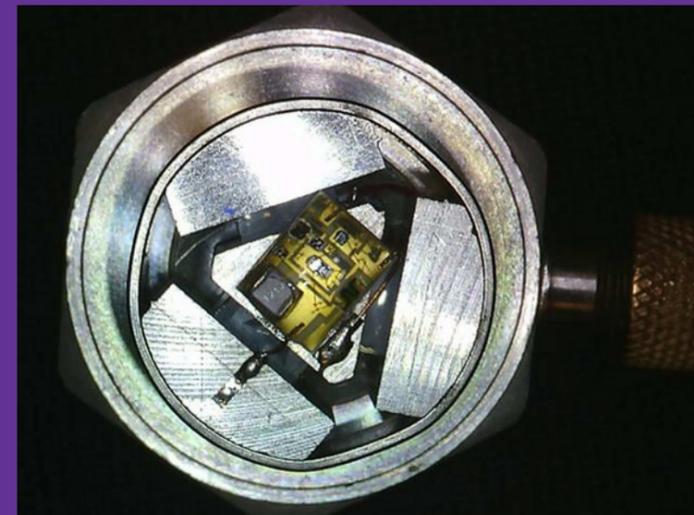
Stennis

Lightweight, Cost-Effective Solution for Structural Measurements

A field-deployable piezoelectric gravimeter

Sensors are typically designed for specific functions, such as detecting leaks or humidity. This can result in a time-consuming, costly cycle of design, test, and build, since there is no real standard sensor building block.

To help solve this, innovators at Stennis Space Center developed the piezoelectric gravimeter (PEG) to serve as the foundation for a wide variety of sensing applications. PEG is a field-disturbance sensor system that includes a piezoelectric element for generating mechanical energy when electrically excited and for generating electrical energy when mechanically deformed.



Benefits

- Small, portable, and lightweight
- No specialized training is required to operate
- Capable of highlighting and detecting minuscule differences within large datasets

Applications

- Industrial structures
- Automotive
- Chemical
- Petroleum



Benefits

- Recycles carbon dioxide emissions as carbon
- Carbon additive makes the cement more durable, particularly against salt
- Uses waste heat from the manufacturing process to capture carbon from emissions

Applications

- Improved materials for construction
- Manufacturing

Improved Cement Performance

Carbonated cement for production of concrete with improved properties

Innovators at Marshall Space Flight Center have developed a new cement composition and manufacturing method that reduces carbon dioxide emissions in cement manufacturing while also improving the performance of the cement.

Building on their expertise in life-support oxygen-control systems for spacecraft, the researchers created a process that reduces carbon to a solid form from captured emissions. The carbon is then added to the cement product, making it more durable against salt typically used to reduce ice on structures and roadways.

Remote Sensing Toolkit

Online portal offers easy access to NASA Earth-observation data

NASA's policy making remote sensing data freely and publicly available has long benefited the scientific community, other government agencies, and nonprofit organizations – but there is significant untapped potential for commercialization. NASA's Technology Transfer program has created an online resource to promote wider use of this data and the software tools needed to work with it.

Through its constellation of Earth-observation satellites, NASA collects petabytes of data each year. With the Remote Sensing Toolkit, users will now be able to find, analyze, and use the most relevant data for their research, business projects, or conservation efforts. The toolkit provides a simple system that quickly identifies relevant sources based on user input. The toolkit will help users search for data, as well as ready-to-use tools and code to build new tools.



Benefits

- Easy-to-use data
- No cost
- Centralized online repository with unified file formats
- Includes data from more than 20 satellites and missions
- Available to U.S. and foreign nationals

Applications

- Precision agriculture
- Crop forecasting
- Conservation
- Resource management
- Natural disaster planning and response



**NASA TECHNOLOGY
TRANSFER PROGRAM**

National Aeronautics and Space Administration

Technology Transfer Program

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