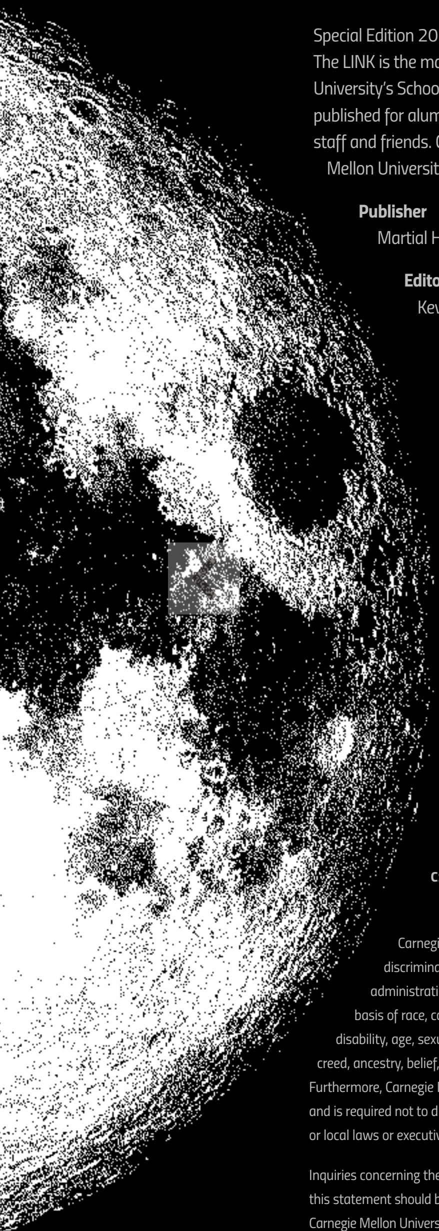
CARNEGIE MELLON UNIVERSITY

A LEGACY IN

SPACE

A SPECIAL EDITION OF
THE LINK MAGAZINE

theLINK



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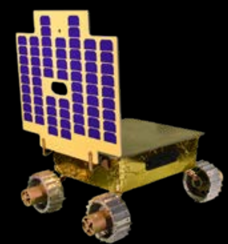

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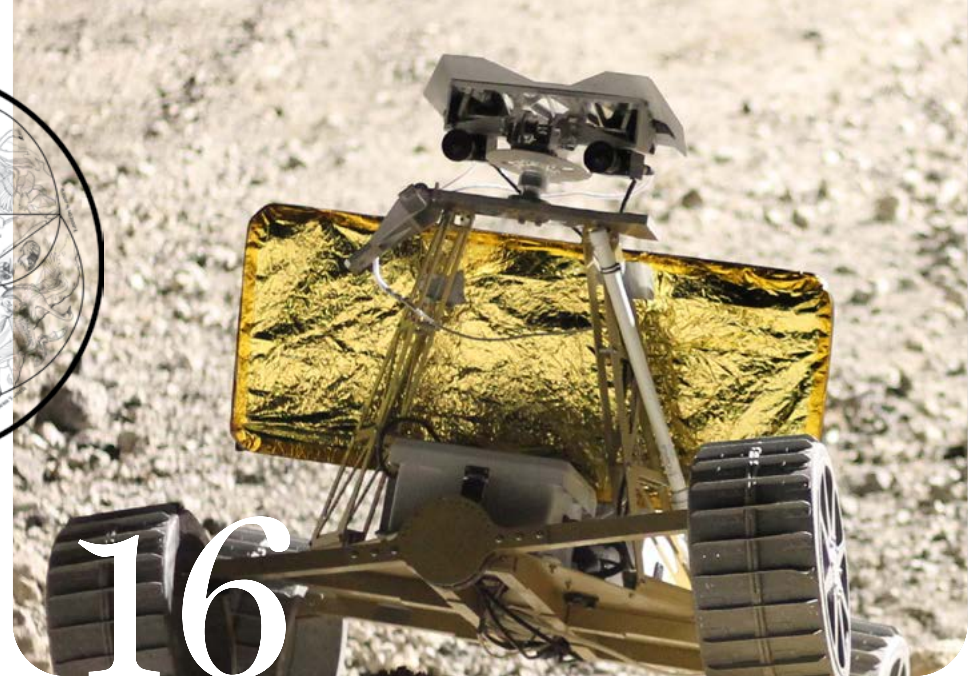
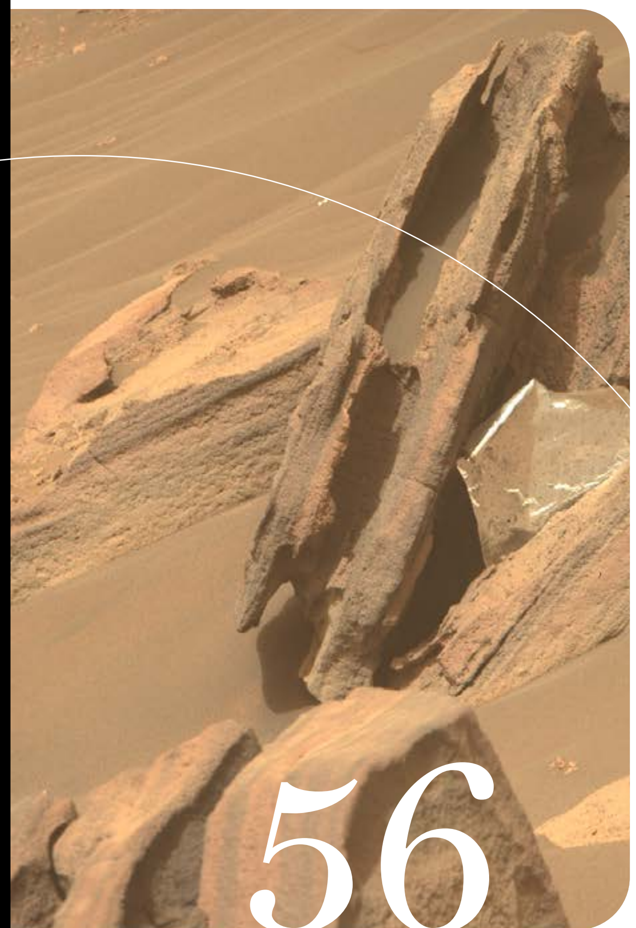




Today, it is difficult to find a major aerospace program that doesn't have some personal traceability back to CMU.

It is December 1992, and we are perched at the top of Mt. Erebus, an active volcano on Ross Island, just a short hike across the ice from the main continent of Antarctica. The rim is a thin, two-yard-wide ledge that encircles the quarter-mile diameter crater. Covered with snow, ice and loosely frozen crystals of volcanic rock, the footing feels even more precarious than it looks. A slip one way, and it is an 850-foot fall into the crater and down to the open lake of molten lava exposed at the bottom of this huge portal into the mountain. Slip the other way, and it will be a long 12,400-foot tumble down the unbroken slope of the volcano's exterior, only stopping when you get to the frozen surface of the Ross Ice Shelf more than two miles below. Both possibilities are at the front of our minds as the volcano "burps" and throws a spray of lava bombs and "Pele's Hair," thin strands of solidifying volcanic glass, high over our heads.

Admittedly, when 2,200°F molten rock is being tossed about it can be a bit difficult to remember that the security of your position on the rim ledge is not the reason you are here. The primary goal is to deploy and operate Dante, an eight-legged walking robot, inside the crater where it is intended to rappel down the near-vertical crater walls to the lava pool below, collecting science samples and data along the way.

Developed and built by the CMU Field Robotics Center (FRC), Dante is an eight-legged walking robot, a technology proof-of-concept and planetary exploration prototype. Under a grant from NASA, Dante has been developed to create and validate multiple technologies that will one day make their way into robotic explorers destined for Mars. The CMU field team of Red Whittaker, Dave Wettergreen, Eric Hoffman and Dan Christian are backed up with additional support from NASA, the National Science Foundation and the New Mexico Institute of Mining and Technology, as well as the remote operations team back at CMU in Pittsburgh.

Pulled together in just over a year — from initial concept to deployment — the Dante project is attempting to demonstrate that the technologies that NASA will target for use on the Red Planet are ready for some of the most severe environments anywhere. And the chosen way to do that is to field trial an actual remote science mission in some of the most extreme environments on Earth — inside the high-altitude craters of high-latitude active volcanos.

From the mid-1980s through the 1990s, the nascent discipline of field robotics was burgeoning, driven primarily by fledgling applications in subsea and space environments. NASA had developed a huge interest in space robotics capabilities, motivated by the potential for robotic rovers for planetary surface exploration and on-orbit robotic servicing systems typified by the Flight Telerobotic Servicer (FTS) system for the International Space Station. Resulting from this was a national effort to develop enabling technologies to move applications of robotic systems from rigidly defined factory floor settings to highly unstructured environments with unpredictable interactions.

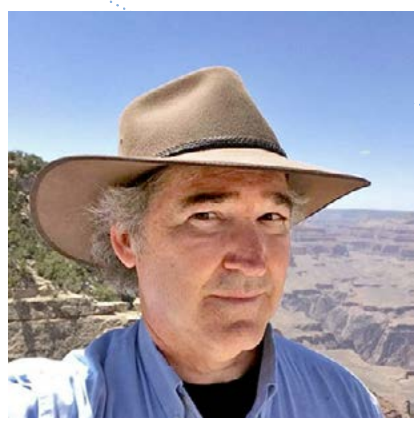
At least in part, leadership of this push was provided by the NASA Telerobotics Intercenter Working Group (TRIWG), which identified needed investments, technical assessment and strategic guidance to the national robotic programs. The FRC took their place as one of only two university participants in TRIWG, based on the existing FRC leadership in applications that bridged the national needs. For more than a decade and a half, TRIWG leveraged the internal NASA field center knowledge of the development of space systems with the FRC's ability to instantiate audacious implementations of the generation-after-the-next versions of creative TRIWG visions.

With the direct, hands-on collaboration of the CMU Field Robotics Center and the NASA field centers, the TRIWG community became one of the most productive and cohesive discipline technology development programs in the nation. The team created fundamental robotic technologies that were critical to almost every space robotic system flown by NASA since then. The direct offspring of TRIWG include the Mars Pathfinder rover Sojourner, the AERCam free-flying space camera platform, the Mars Exploration Rovers Spirit and Opportunity, the robotic arms for the Phoenix and Insight Mars Landers, Robonaut 2 flying on International Space Station, the Perseverance and Curiosity rovers, the Lunar Electric Rover, the National Robotics Engineering Center, and too many component technologies to mention.

Dante II at the Mt. Spurr volcano in Alaska.

By the end of the Dante deployment on Mt. Erebus, the CMU team successfully demonstrated multiple robotic technologies on the mountain. Techniques including walking with intrinsic gait planners, advanced control execution, precursors to the D* traverse planner, single actuator drives for multiple legs, robotic rappelling for descent of vertical slopes, capacireflector proximity sensors for footfall placement, remote robot operations via the U.S. Tracking and Data Relay Satellite System (TDRSS), and many others, were all shown to be viable for use in extreme environments. Although the plan for remote science operations at the bottom of the M.t Erebus crater was cut short by a severed fiber optic cable, this capability was demonstrated 18 months later by Dante II in the crater of the Mt. Spurr volcano in Alaska, successfully concluding the objectives of the project.

But even more important than the technologies validated through the Dante project and similar endeavors, the real products of the last 30 years of SCS/FRC projects were the people that emerged from the efforts. The program has produced an amazing legacy of students who have perfused throughout the aerospace community. Today, it is difficult to find a major aerospace program that doesn't have some personal traceability back to CMU, the TRIWG program and the teams they built. The students, researchers and developers have disseminated the last 30 years of knowledge they created out to the aerospace world in the most effective way possible — by graduating into that community and becoming the engineering, science and design leaders that are now guiding the next 30 years of space exploration. ■



Dave Lavery
Program Executive for Solar System Exploration
Science Missions Directorate, NASA Headquarters

CMU Heads to the Moon

MISSION:

Ignite Modern-day Planetary Exploration

AARON AUPPERLEE

Raewyn Duvall looks at the Moon differently these days, even though she feels she rarely looks at all.

As the commander of the Iris mission, Duvall hasn't had much time to step out at night and gaze up. During the months leading up to the launch of the shoebox-sized rover, the Carnegie Mellon University team has been busy: a bevy of tests needed before flight — vibration, radiation, thermal, electromagnetic — all passed with flying colors, nights spent hunched over circuit boards with soldering irons completing last-minute reconfigurations, and software update after software update. Even after the rover was bolted onto its lander and out of the team's hands, they were updating software.

"I pointed up at the Moon and shouted, 'I can see our landing site." Raewyn Duvall

But in September of 2022, seven months or so before Iris' expected launch date, Duvall was at a wedding and stepped outside with some friends. The Moon beamed big and bright.

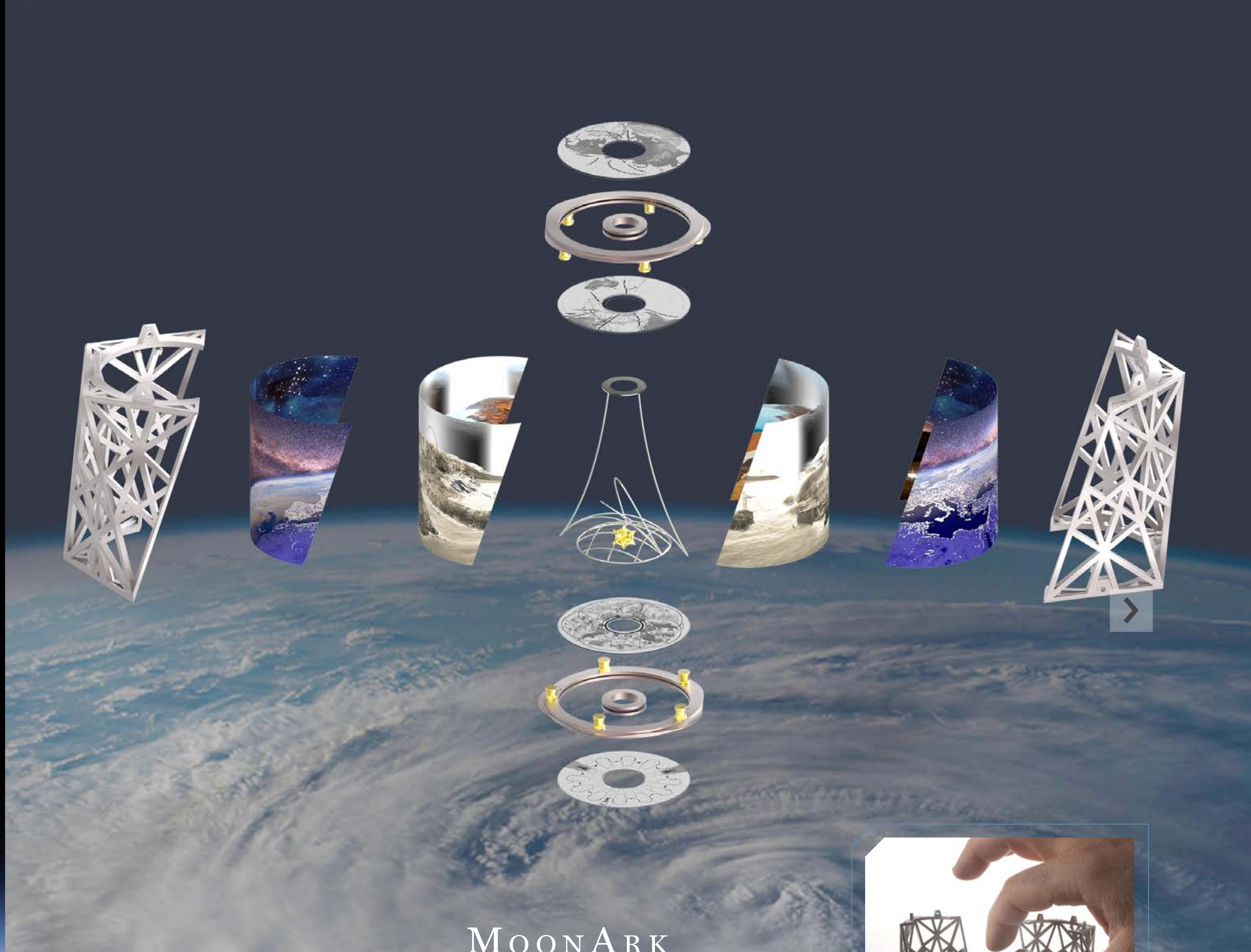
"I pointed up at the Moon and shouted, 'I can see our landing site,'" Duvall said. "It was crazy to know that's where we'll be and knowing that when we're there, we'll be the first Americans back on the Moon."

CMU, in a collaboration cutting across the School of Computer Science, College of Engineering, School of Design and other departments, is going to the Moon. Iris is scheduled to lift off this year and after a month-long journey to the Moon, deploy from its lander and send back images of the lunar surface.

Catching a ride on the same rocket and lander as Iris is MoonArk, an intricate titanium, platinum and sapphire artifact containing hundreds of images, poems and music relating to earthly arts, humanities, science and technologies.

A few years later, **MoonRanger** will start to explore the Moon's south pole, bringing an unprecedented level of autonomy to the lunar surface.

The upcoming lunar missions are ambitious. They will herald America's



MoonArk

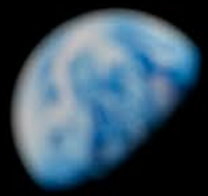
At Carnegie Mellon University, collaboration is in our DNA. The MoonArk project embodies and exemplifies our collaborative efforts, weaving human narratives of the arts, humanities, sciences and technologies into an integrated sculpture set to arrive on the Moon aboard Astrobotic's mission to land the Iris Rover. The coordinated effort of 18 universities and organizations and more than 250 contributing artists, designers, educators, scientists, engineers, choreographers, poets, writers and musicians, MoonArk is designed to weave a complex narrative of humanity.

The human connection to the Moon transcends known time. We have long pondered the Moon, wondered how it stirs the tides, affects the growth patterns of life and how it has always been our gateway to the heavens and space exploration. MoonArk's design directs our attention from the Earth outward, into the cosmos and beyond, and reflects back to Earth as an endless dialogue that speaks to our context within the universe.

In order to be afforded passage on the journey, MoonArk has been designed to be exceedingly small. Four 2x2 inch chambers make up its cargo hold, all weighing in at a mere nine ounces. Yet despite its modest size, MoonArk is intricate, containing hundreds of images, poems, pieces of music, nano-objects, mechanisms and earthly samples.

To survive the trip and become a permanent artifact on the Moon, MoonArk has been fabricated of titanium, platinum and sapphire — materials sturdy enough to have successfully passed space-readiness thermal and vacuum testing. In fact, building MoonArk instigated original innovation and invention of digital fabrication techniques, ultra-high-resolution imaging and innovations in material science and digital storage techniques.

Two identical MoonArks have been created, one headed to the Moon and one to remain here on Earth, as part of the permanent collection of the Smithsonian National Air and Space Museum.



return to the Moon while planting a flag for university-led planetary exploration. They will lay claim to firsts. They will take risks NASA and other space agencies shun, incorporating new materials and new technology. And they will inspire the next generation looking toward space with wonder.

"It's transformational," said CMU planetary robotics pioneer William "Red" Whittaker, the Founders University Research Professor in the Robotics Institute. "We're not doing this in the same old same old sort of way. This is a revolution of miniaturization, of high-end capabilities, and of lean development that you can't get elsewhere.

"It is very special, and it's auguring in the way to come."

CMU planetary robotics pioneer William "Red" Whittaker, the Founders University Research Professor in the Robotics Institute and co-founder of Astrobotic.

"It's transformational. This is a revolution of miniaturization, of high-end capabilities, and of lean development that you can't get elsewhere."

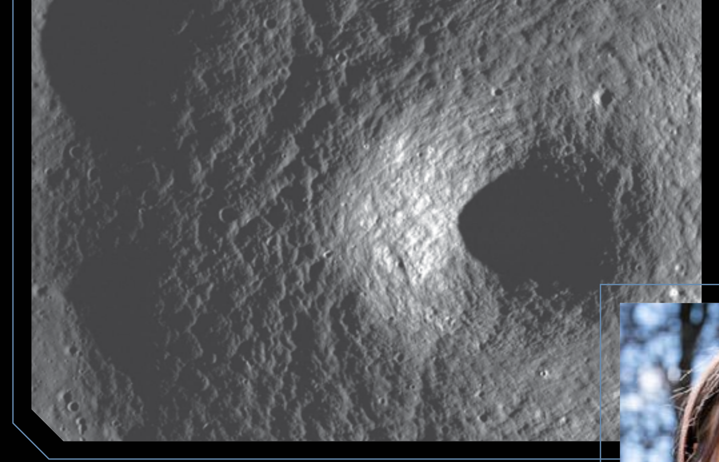


Image courtesy of NASA

Volcanoes in Lacus Mortis, the Peregrine lander's touch down location on the Moon's near side.

Raewyn Duvall (ECE 2019) Research Associate in the Robotics Institute and Commander of the Iris Mission.

_A MISSION OF FIRSTS

When **Iris** rolls over the Moon's surface on its distinctive bottle cap wheels, it will mark several firsts in lunar exploration.

The tiny rover is scheduled to lift off from John F. Kennedy Space Center this year aboard Astrobotic's Peregrine Lander and atop a United Launch Alliance (ULA) rocket. After a 30-day flight to the Moon, the lander will descend to Lacus Mortis, the Lake of Death, a plain of lava flows in the northeastern part of the near-side of the Moon. Upon landing, Iris will deploy from Peregrine and begin its 60-hour mission, taking photos as it moves across the surface.

"There's going to be some intense moments," Duvall said.

Iris will be the first American rover on the Moon. Yes, American astronauts did drive Lunar Roving Vehicles on the lunar surface during the final Apollo missions, but Iris will be America's first robotic rover, the first rover in the spirit of modern-day Martian rovers like Curiosity and Perseverance, on the Moon. Other nations have put rovers on the Moon. The Soviets did it first in 1970 with Lunokhod. Most recently, China successfully deployed rovers on the Moon while India tried but lost its Pragyan rover when its lander crashed.

Depending on the final launch date, it will also be among the first student-developed rovers on the Moon. About 300 students — primarily undergraduates, a few master's students and Duvall, the only Ph.D. student — have worked on Iris or projects leading up to Iris. The CubeRover was one such student project that started in 2017 and paved the way for small, lightweight rovers. As Iris evolved from prior research projects, faculty stepped back.

"People like Red and others really wanted to make sure it was the students making the decisions and driving the design and development processes," Duvall said.

The rover will also be the smallest and lightest rover to land on the Moon. Its size and, more importantly, its weight, drove many of the engineering decisions and challenges the team faced. Iris weighs just two kilograms and is the size of a shoebox. Yutu-2, China's rover on the far side of the Moon, weighs 140 kilograms and is a meter and a half tall. Perseverance, the latest NASA rover to land on Mars, weighs 1,025 kilograms and is the size of a small car.

To make weight, Iris needed more firsts. Since the actuators and batteries — six total, each no larger than a tube of lipstick — make up most of its weight, the rest of the rover had to be as light as could be. Iris will be the first rover with a carbon fiber chassis and carbon fiber wheels. Aluminum is the preferred material for planetary exploration. The bottle cap-shaped wheels themselves are a novel design.

"This mission is about proving that we can do it, that students can go to the Moon, that small rovers can make it there," Duvall said. "The Moon has always been this Apollo-era ideal for people. But as soon as we do this, as soon as there is a private landing, and we show that a university, that a team of students, can put a rover on the Moon, it is suddenly possible for everybody."

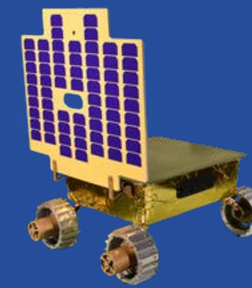
Tim Angert, the RI Machine Shop Manager, integrating the Iris rover on the lander deck.

Getting to the Moon will require a few firsts as well. The launch will be the first of the United Launch Alliance's (ULA) Vulcan Centaur rockets, likely the first rocket to use methane as fuel. It's also the first flight for Astrobotic, the CMU spinout company aiming to usher in an era of private lunar missions.

The mission's firsts don't keep Duvall up at night. She is confident the ULA rocket and Astrobotic lander will deliver Iris safely to the Moon. She is confident Iris will deploy and send back stunning imagery that changes what is possible. But most importantly, she's confident in her team. (To see the Iris Team, see the Mission Control story on page 26.)

"We've done everything we can to make this a successful mission," Duvall said. "What keeps me up at night is making sure we continue to do everything possible to give Iris the best possible chance to succeed up there."

And while Iris is up there, operational on the lunar surface, Duvall doesn't intend to sleep.



_MOVING FAST, TAKING RISKS

MoonRanger intends to hit the ground running. It has to.

The suitcase-sized rover's target is the south pole of the Moon, and it will have a dual mission once it lands and lifts its sail-like solar panel to the sun. The rover aims to demonstrate that autonomous navigation technology developed for Earth's self-driving cars will work on other planets. It will also carry an instrument designed to test for hydrogen in the lunar soil, potentially indicating the presence of ice.

MoonRanger doesn't have a launch date set. Originally, the team expected their rover to fly and land on the Moon in late 2023. Those plans, however, were grounded when Masten Space Systems, the company building the lander, filed for bankruptcy in July 2022. NASA remains committed to the MoonRanger program and getting the rover to the Moon.

When MoonRanger does land, its missions could change the course of planetary exploration. If MoonRanger can show that autonomy works on the Moon, it could enable a new generation of autonomous rovers and usher in automated science in space. (For more on automated science in space, see the story on page 56.) And the ice that the Neutron Spectrometer System (NSS) locates will have great scientific value and serve as a valuable resource for future missions. But the rover has an extremely limited time to complete these missions before the light disappears from the southern pole and with it MoonRanger's power and heat.

"We've got 10 days," said Whittaker, who is leading the development of MoonRanger. "And this rover has the ambition to roam far, measure and map and to do it again and again, so there is a need for speed."

MoonRanger's comparatively short mission — most rovers land on their planets with intentions to operate for years — will be dictated by its location and the lunar day. One lunar day is about 29 Earth days, and each pole is in sunlight for about half that. Knowing that MoonRanger will not deploy right at polar dawn and that shadows from surrounding peaks will obscure the light for periods of time, the team estimates they have 10 to 12 days to complete their mission.

> *"This mission is about proving that we can do it, that students can go to the Moon, that small rovers can make it there."* Raewyn Duvall

"MoonRanger has the kind of driving autonomy that CMU has specialized in for decades." Red Whittaker

Planetary rovers don't move fast, and they don't cover a lot of ground. The Perseverance rover on Mars has a top speed of 4.2 centimeters per second but spends most of its time stationary. Yutu-2, the Chinese rover on the Moon, traveled about a kilometer in its first year there. MoonRanger has a top speed of five centimeters a second, and the team hopes it can cover about a kilometer during its short mission. Rovers move slowly. Speed comes in decision making.

Before the current fleet of planetary rovers moves, teams on Earth digest volumes of data, meticulously plan the route and beam it across space for execution. This takes time, which MoonRanger doesn't have. What MoonRanger has is autonomy.

"It has the kind of driving autonomy that CMU has specialized in for decades, and it can bring it to bear such that it stays on the move," Whittaker said.

MoonRanger's autonomy will allow it to chart its own path to reach waypoints sent to it by the team on Earth. The rover will receive the waypoint, venture out from the lander — its NSS instrument ticking away like a Geiger counter as it gathers data — return to the lander, receive the next waypoint and go out again. The rover's autonomy will be put to the test. MoonRanger is so small and so light that it can't carry a radio that can communicate with Earth. Once it ventures beyond the range of the lander, MoonRanger is on its own.

Enabling the rover's autonomy requires an impressive mix of hardware and software. A set of stereo cameras the rover uses to see are designed to work in both brilliant light and total darkness. Images from these cameras must be processed quickly onboard to keep it moving, requiring impressive computing power for its size and use of a graphics processing unit, a standard microprocessor in high-end terrestrial computing systems but nearly unheard of in space, where most crafts carry 1990s-era computer chips.

The MoonRanger team took the algorithms developed over decades at CMU for autonomous vehicles on Earth and rewrote them to work with NASA's core flight system. This required vast amounts of software engineering, software test planning, verification and validation. The process took a year.

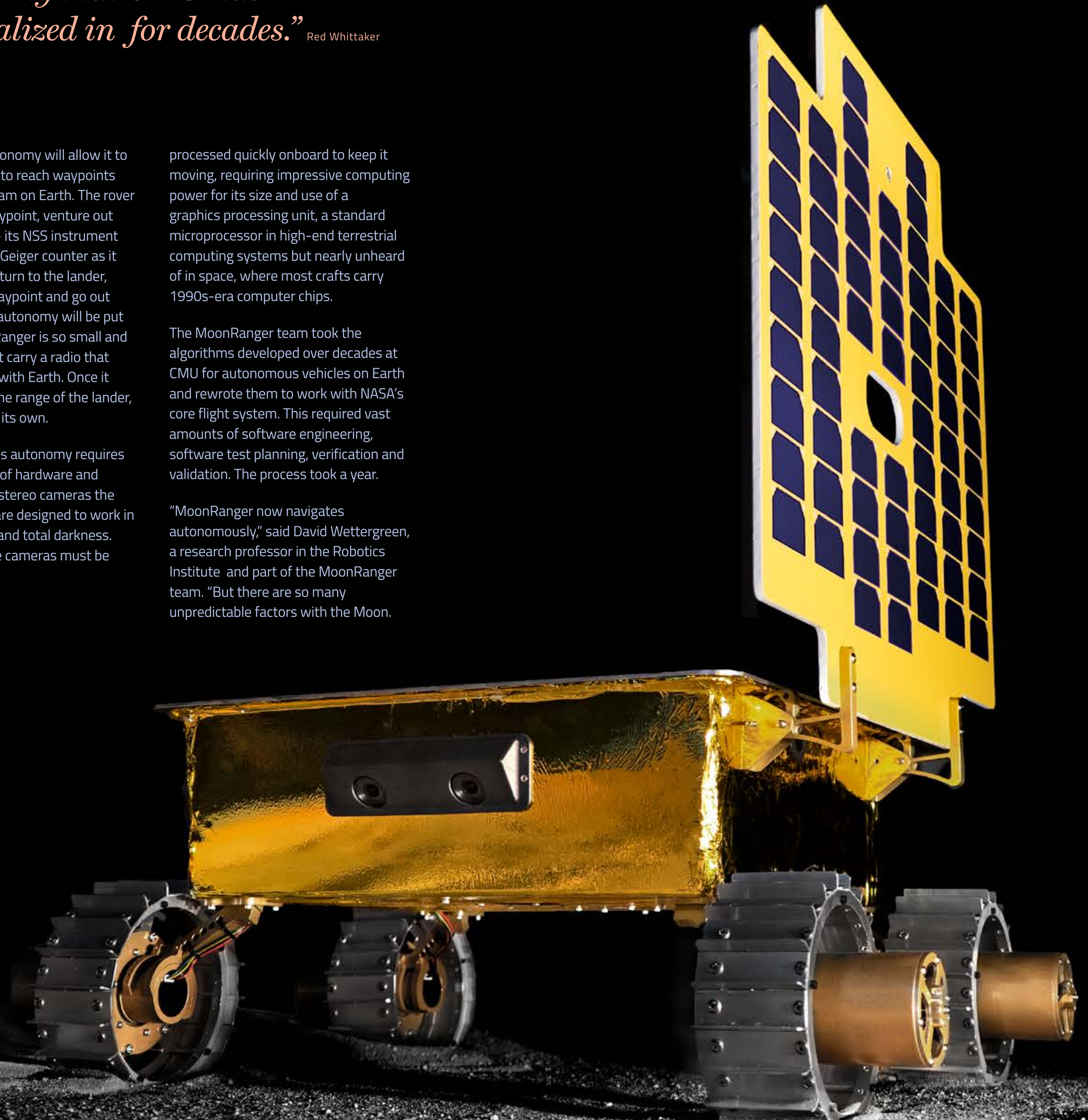
"MoonRanger now navigates autonomously," said David Wettergreen, a research professor in the Robotics Institute and part of the MoonRanger team. "But there are so many unpredictable factors with the Moon. We're trying to be better prepared for situations that might occur. It's never going to be perfect."

Testing of MoonRanger's software happens constantly. The team developed a simulator where the rover covered six kilometers on the Moon in one weekend. The team also built a sandbox in the high bay of the Planetary Robotics Lab. There, a copy of MoonRanger drives around rocks and other obstacles.

Autonomous navigation isn't new in planetary exploration — research at CMU stretches back into the 1980s and Curiosity used it on Mars in 2013 — but the perception of its risk remains. MoonRanger is embracing those risks to demonstrate what's possible.

"Maybe that's all that's needed to break that perception," Wettergreen said. ■

David Wettergreen, research professor in RI and part of the MoonRanger team.



With MoonRanger's top speed of five centimeters per second, the team hopes the rover will cover about a kilometer during its mission.

CARNEGIE MELLON
SCHOOL OF
COMPUTER SCIENCE

EDGAR MITCHELL (ENG 1952) – BECOMES ONE OF 12 ASTRONAUTS TO WALK ON THE SURFACE OF THE MOON.

1971

A Legacy

OF RESEARCH, EXPLORATION AND IMPLEMENTATION IN SPACE

KEVIN O'CONNELL

FROM ESTABLISHING THE FIELD ROBOTICS CENTER TO STUDENT-DESIGNED ROBOTS EXPLORING THE MOON (AND BEYOND), the School of Computer Science has played an integral and increasing role in space exploration and advancement these past 40 years. While computing, robotics and many other technologies have been developed by SCS students, faculty and researchers, they represent only part of the story. "SCS in Space" might more accurately be labeled "CMU in Space," or "CMU and our partners — regional, national and international — consisting of government agencies, corporations and the brightest universities," all coming together to reach for the stars. No one accomplishes the projects in these pages single-handedly.

Just as daunting as the task of capturing the breadth of SCS' contributions made to modern space exploration, these pages can never fully catalog the depth of research, scholarship and influence as they pertain to current efforts. The topic is too broad, with contributions and partnerships across the university — many of which live outside of SCS entirely.

Still, it remains important that we acknowledge the parts we have played in this great journey up to this historic point, and those we will play in the years to come. At its core, SCS' role accurately reflects the best of CMU generally: a thirst to know more and do what it takes to get the job done; the recognition of value on partnerships and building the best teams with multidimensional, multidisciplinary members; and, guiding those teams toward innovative thinking and problem solving.

> As unprecedented advances drive societal and economic transformation, the United States must double down on our national investments in research and innovation to secure our global competitiveness and address complex societal challenges. This includes continued support of our nation's space programs, where interdisciplinary partnerships can seed ideas and innovations that not only push the boundaries of discovery, but also catalyze economic growth and job creation."

FARNAM JAHANIAN, *CMU President*

SCS in Space

1984

JUDITH RESNIK (ENG 1970) – ENGINEER AND MISSION SPECIALIST ON THE SPACE SHUTTLE DISCOVERY. THE SECOND WOMAN AND FIRST JEWISH-AMERICAN IN SPACE, RESNIK PERISHED WHEN CHALLENGER EXPLODED IN 1986.

1990

AMBLER - A WALKING ROBOT DEVELOPED AS A TESTBED FOR RESEARCH IN WALKING ROBOTS OPERATING IN RUGGED TERRAIN.

1991

JEROME APT MADE TWO SPACEWALKS WHILE ABOARD SPACE SHUTTLE ATLANTIS FOLLOWED BY MISSIONS ABOARD SPACE SHUTTLE ENDEAVOR BEFORE JOINING THE FACULTY AT CMU.

1994

DANTE II - A TETHERED WALKING ROBOT FOR SCIENCE MISSIONS IN ACTIVE VOLCANOES, EXPLORED ALASKA'S MT. SPURR VOLCANO.

1994

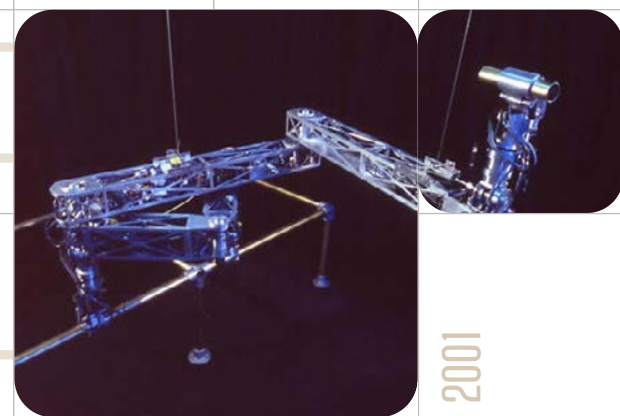
RATLER - PROTOTYPE ROVER BUILT TO DEMONSTRATE TECHNOLOGIES THAT COULD ENABLE ROBOTIC LUNAR MISSIONS.

1997

NOMAD - BUILT FOR AUTONOMOUS EXPLORATION OF PLANET-LIKE DESERTS; PIONEERED SPHERICAL VISION AND LONG-RANGE NAVIGATION.

2000

AMES RESEARCH CENTER'S NASA RESEARCH PARK / CMU SILICON VALLEY COLLABORATION FORMED, A PARTNERSHIP TO DEVELOP NEW APPLIED INFORMATION TECHNOLOGY.



2001

SKYWORKER - AN ASSEMBLY, INSPECTION AND MAINTENANCE ROBOT FOR ORBITAL STRUCTURES.

Achieve

LEADERSHIP IN THE CMU-LED APPROACH TO SPACE EXPLORATION

Space travel remains expensive. At times, prohibitively so. Today, individual billionaires fund their own space programs. While we can debate the merits of this approach, leadership at CMU remains focused on partnerships across the academic, government and corporate sectors to achieve optimal results. The best minds, the best funding and the best scientists and engineers all working together toward commonly outlined and mutually beneficial goals.

CMU President Farnam Jahanian is a national leader in advocating for and leveraging federal funding in science and innovation to address national priorities, expand our knowledge of the world and enhance U.S. competitiveness.

"As unprecedented advances drive societal and economic transformation, the United States must double down on our national investments in research and innovation to secure our global competitiveness and address complex societal challenges," said Jahanian. "This includes continued support of our nation's space programs, where interdisciplinary partnerships can seed ideas and innovations that not only push the boundaries of discovery, but also catalyze economic growth and job creation."

Carnegie Mellon President Farnam Jahanian addressed the House Science, Space and Technology Committee on April 15, 2021, about our nation's innovation ecosystem. The full record of Jahanian's remarks before congress and the entirety of his "Reimagining Our Innovation Future" testimony can be found at

https://science.house.gov/hearings/reimagining-our-innovation-future?utm_medium=email&utm_source=FYI&dm_i=1ZJN,7BQOW,486VWQ,TPZB5,1

HYPERION: SUN-SYNCH - A SOLAR POWERED ROVER THAT PROVED THE CONCEPT OF SUN-SYNCHRONOUS NAVIGATION IN THE CANADIAN HIGH ARCTIC.

2001

2002

HIGH-DEPENDABILITY COMPUTING CONSORTIUM (HDCC) PARTNERSHIP DEVELOPED TO IMPROVE NASA'S CAPABILITY TO CREATE DEPENDABLE SOFTWARE.

THE EVOLVING LANDSCAPE OF DISCOVERY

The Apollo 17 mission in 1972 marks the last time humans stepped foot on the Moon. Originally, 20 Apollo missions had been planned, but funding cuts for NASA forced cancellation of the final three missions. Additionally, the goal of being the first to put a human on the Moon, the original "Space Race," had been achieved.

While studying the Moon with future human missions has always been NASA's goal, SCS, with its long history of field robotics, became the perfect partner for this next phase of exploration — space exploration via robotics. As RI research professor David Wettergreen explained, this became CMU's moment to excel.

"Our legacy in space will be for innovation in robotics," said Wettergreen. "Since our first work in the 1990s we have sought to create novel, effective robot designs, to advance functional autonomy in exploration and to envision missions made possible by our technologies."

Wettergreen pointed to many of the technologies and landmarks noted in the timeline of SCS-inspired work in partnership with NASA, such as long-distance navigation, sun-synchronous routes and lunar ice and pit exploration, as examples of the great impact that SCS has contributed to get the National space program to where it is today.

These past and current contributions have cemented SCS' legacy as a partner in all facets of future space exploration missions. One of SCS' largest contributions going forward comes from our thought leadership in world-changing theoretical work, exemplified by Wettergreen, in the application of automated science for planetary exploration. (Read the full story on automated science in space on page 56.)

Teamwork

2004

ZOE - EQUIPPED WITH SPECIALIZED SENSORS TO SEARCH FOR LIFE, ITS SOLAR CELLS COLLECT ENERGY AND PLAN ACCORDINGLY TO MAXIMIZE SCIENCE RETURNS.

2006

TRESTLE - DEVELOPED THE ARCHITECTURAL FRAMEWORK NECESSARY TO COORDINATE MULTIPLE ROBOTS PERFORMING COMPLEX ASSEMBLY PROJECTS.

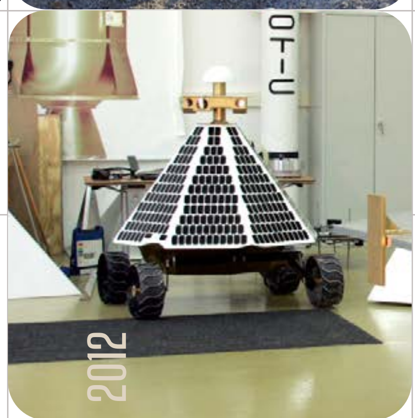
SCARAB - A PROTOTYPE ROVER FOR LUNAR POLAR EXPLORATION, IT ADJUSTS BODY POSTURE FOR ASCENT AND DESCENT OF CRATERS AND TO POSITION CORE SOIL DRILLING.

2007

2012

2007

ASTROBOTIC TECHNOLOGY – FOUNDED BY RED WHITTAKER AND ASSOCIATES WITH THE GOAL OF WINNING THE GOOGLE LUNAR XPRIZE, THE COMPANY'S PEREGRINE LUNAR LANDER IS SCHEDULED TO REACH THE MOON IN 2024.



2012

RED ROVER - THE SHAPE OF THIS MOON ROVER MODERATES EXTREME LUNAR TEMPERATURES WHILE GATHERING SUN POWER AND REJECTING HEAT.

MARS ROVER DRIVER – VANDI VARMA (SCS 2005) DRIVES HER FIRST ROVER CURIOSITY ON THE SURFACE OF MARS. VARMA HAS DRIVEN FOUR MARS ROVERS TO DATE (2022).

Read an update on the Mars Rover and the Mars 2020 mission on page 66.

EXPLORATION ROVERS

The Iris and MoonRanger missions feature students working alongside faculty in developing the robotic moon rovers — as well as staffing the missions — all culminating from decades of building prototypes and testing each through phases of mobility, autonomy and functionality.

The builders of the AI, computer vision and lunar landing guidance systems are involved at every level, from conceptualization of sending astronauts to space and housing them on the Moon to exploring distant planets and returning astronauts safely home.

Perhaps most impressively, our students will command these missions from a Mission Control Center located on campus in the Gates Center for Computer Science. (See the article on page 26.) These achievements deserve recognition and laudation.

Often, it's the theoretical work, or the precursory research that is easiest to overlook. That which is perhaps not as easy to visualize is no less important. Networking, software engineering, AI and security in communications come to mind as examples of such mission critical technologies on which our legacy has been built. According to Martial Hebert, dean of SCS, that work is the foundation on which all our current efforts stand.

MARTIAL HEBERT, *Dean of SCS*

"WE SHOULD THINK OF OUR BODY OF WORK A BIT DIFFERENTLY THAN POINTING TO A SPECIFIC PIECE OF SOFTWARE OR A SPECIFIC ALGORITHM," SAID HEBERT. "IT'S ACTUALLY THE COMPLETE VISION OF AI AND ROBOTICS IN SPACE THAT HAS BEEN INSTRUMENTAL IN PUSHING ALL EFFORTS FORWARD."

2014

ANDY 2 - BUILT FOR THE GOOGLE LUNAR XPRIZE CHALLENGE, MOBILITY TESTS WERE CONDUCTED AT NASA GLENN RESEARCH CENTER ON SIMULATED LUNAR SAND.

2021

GLEN DE VRIES (MCS 1994) CMU TRUSTEE TRAVELS TO SPACE ABOARD BLUE ORIGIN'S NEW SHEPARD SPACECRAFT.

2021

CMU AND ASTROBOTIC ALONG WITH PARTNERING ORGANIZATIONS FORM THE KEYSTONE SPACE COLLABORATIVE TO SUPPORT REGIONAL BUSINESS AND TECHNOLOGY EXPANSION IN SPACE-RELATED OPPORTUNITIES.

2022

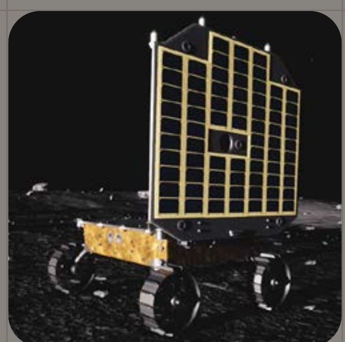
MOONSHOT MUSEUM OPENS IN PITTSBURGH'S NORTHSIDE TO EDUCATE AND SPUR INNOVATION IN SPACE TECHNOLOGY.

2021

LANDER VISUAL SYSTEM (LVS) - ANDREW JOHNSON'S (SCS 1997) WORK ON LVS SAFELY LANDS THE PERSEVERANCE ROVER ON THE SURFACE OF MARS.

2023

IRIS - DESIGNED BY CMU STUDENTS, THE CUBE ROVER ADAPTATION HAS PASSED ITS CRITICAL DESIGN REVIEW BY NASA AND IS ON TRACK TO LAND ON THE MOON.



2023

MOONRANGER – THE SUITCASE-SIZED ROVER DEVELOPED BY CMU AND ASTROBOTIC IN COLLABORATION WITH NASA'S AMES RESEARCH CENTER, TO SEARCH FOR SIGNS OF WATER AT THE MOON'S SOUTH POLE.

2024

GRIFFIN LANDER – ASTROBOTIC'S LUNAR LANDER SELECTED BY NASA TO DELIVER THEIR VIPER ROVER, WHICH WILL INVESTIGATE PERMANENTLY SHADOWED CRATERS ON THE MOON IN SEARCH OF WATER.

"In time, CMU will be seen as the premier planetary space robotics community. Yes, it will be the great missions.

THE FUTURE

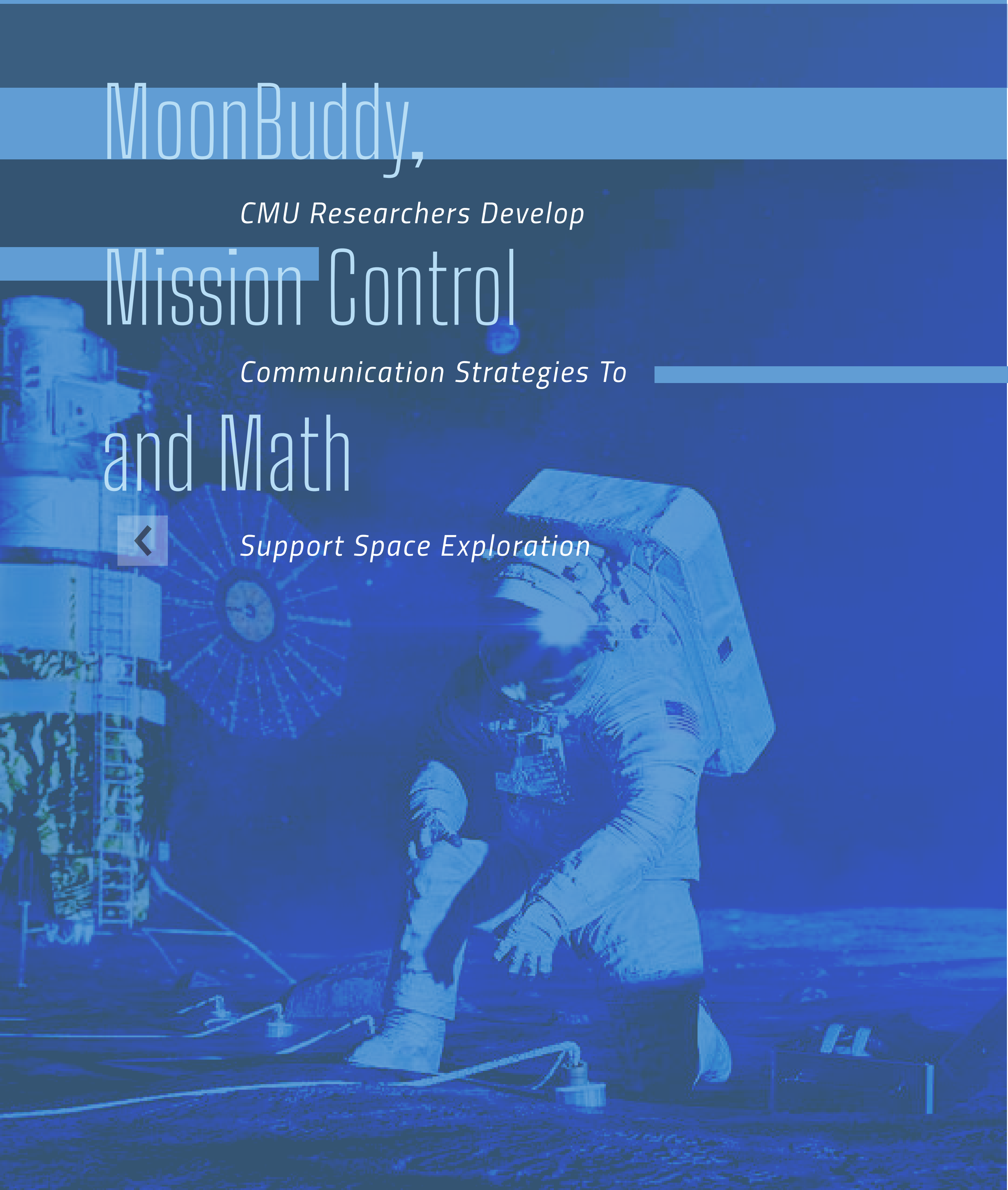
Among the many goals and targeted scientific opportunities of the U.S. Space Program, returning humans to the Moon has reemerged. Much of the scientific research that SCS robots like Iris and MoonRanger will carry out in the upcoming mission have that same goal in mind. Not only for a few days at a time, as was all that was possible for the Apollo missions, but to sustain life on lunar bases and offer communication and networking with lunar satellites, enabling further exploration and research opportunities — to worlds beyond and for the improvement of life on our own planet.

SCS, along with our partners across CMU and the greater academic, corporate and government agencies, intend to remain integral parts of these missions going forward. William "Red" Whittaker, who has been a major contributor to every aspect of this work, gave what will be the final word (for now) about how history will view the contributions and legacy of SCS in space.

Of course, the technology that always marches along, particularly the people that made it great for decades — that pioneered it, the people who are giving of themselves to do these great things now and for generations to come."

RED WHITTAKER

MoonBuddy, *CMU Researchers Develop* Mission Control *Communication Strategies To* and Math *Support Space Exploration*



SUSIE CRIBBS (DC 2000, 2006)

Everyone's heard the old adage that the only way to get to Carnegie Hall is "practice, practice, practice." But how does Carnegie Mellon get to the Moon (and beyond)? Communications, communications, communications.

Right now, students and faculty members are creating new ways for astronauts to connect with one another in space, for people on Earth to stay in touch with rovers and robots off planet, and for securing data as we move into a new era of space exploration.

MoonBuddy Makes a Difference in Future Moon Missions

As a kid, **Angelica Bonilla Fominaya** dreamed of working for NASA. But as someone interested in arts and technology — not straight up engineering or physics — she didn't think it was possible. Then an internship at NASA her junior year in CMU's Bachelor of Computer Science and Arts program helped change her mind. And it led to changes in how astronauts communicate in space.

While a NASA intern, Bonilla Fominaya learned about the agency's Spacesuit User Interface Technologies for Students (SUITS) Design Challenge, which tasked teams of college students with designing and creating spacesuit information displays within augmented reality (AR) environments that could be adapted for use in upcoming Artemis missions to the Moon.

Angelica Bonilla Fominaya, a senior studying computer science and art

Bonilla Fominaya jumped at the opportunity to gather a team and get involved.

David Lindlbauer, faculty member in the HCII

"A couple of my friends are really interested in user interfaces or virtual reality, and we thought it would be fun to try," said Bonilla Fominaya, who served as CMU's team lead. "We spent the fall 2021 semester writing a proposal with the help of Human-Computer Interaction Institute (HCII) faculty member **David Lindlbauer**. We submitted the proposal and it got accepted by NASA and we were like, 'OK, I guess we have to do this now.' "

And do it they did. The team created **MoonBuddy**, an AR interface that will help astronauts navigate the lunar surface by plotting routes and avoiding obstacles, assist with scientific experiments and provide critical support during emergencies.

The team's technology incorporates voice control into the AR interface. With MoonBuddy, an astronaut could ask for their location or the location of crew members and see that information layered on a heads-up display. During sample collection, an astronaut could ask MoonBuddy to record a rock in their hand and show data from a visual analysis on the display. In the event of an emergency, MoonBuddy could share crew member vitals and locations.

"NASA doesn't yet have a system that puts all this information in one place where it is easily accessible by astronauts. Augmented reality of this type hasn't existed in space travel

> "I do think that the things we came up with in the challenge help build the foundation for the types of ideas that NASA will have when they're developing the interfaces for the new space suits." Angelica Bonilla Fominaya

before," Bonilla Fominaya said. "We're developing a novel interface that could actually be used in space exploration."

The CMU team — comprised of students studying augmented and virtual reality, human-computer interaction, information systems, cognitive science, computer science, and art — worked with NASA staff throughout the project. The project culminated in a trip to NASA's Johnson Space Center in Houston this past spring to test MoonBuddy with NASA assets and people.

The team essentially walked around the space center's Rock Yard — a multi-acre test site that simulates lunar and Martian terrain — with a NASA engineer, giving them instructions for using their technology.

It went well. Eventually.

"The first day we were there, we got absolutely demolished, because we had a lot of issues figuring out how to work as a team to make it go smoothly," Bonilla Fominaya said. Frazzled and stressed — and maybe a little intimidated by going behind the veil at the space center — the team struggled with how to give their user appropriate instructions for using the interface. Day one feedback? Work better as a team.

"So we had to refactor," Bonilla Fominaya said. Luckily, the testing schedule gave teams a day between initial testing and their final presentation to work out kinks and bugs. The MoonBuddy team hunkered down and got to work. "We decided to write a good script," Bonilla Fominaya said. "We decided to be calm and collected when we were presenting what we had. Because we had a good interface. Everything worked." So they wrote clear testing instructions and a better script for their presentation, which paid off.

"By the end of it, we had something that worked really well and was really effective," Bonilla Fominaya said.

SUITS has officially ended, but MoonBuddy's work continues.

With NASA's blessing, the team wrote a paper that was accepted to the ACM Symposium on User Interface Software and Technology (UIST 2022). And while there's no guarantee their technology will land on the Moon with the upcoming Artemis missions, Bonilla Fominaya remains optimistic that their work will make a difference.

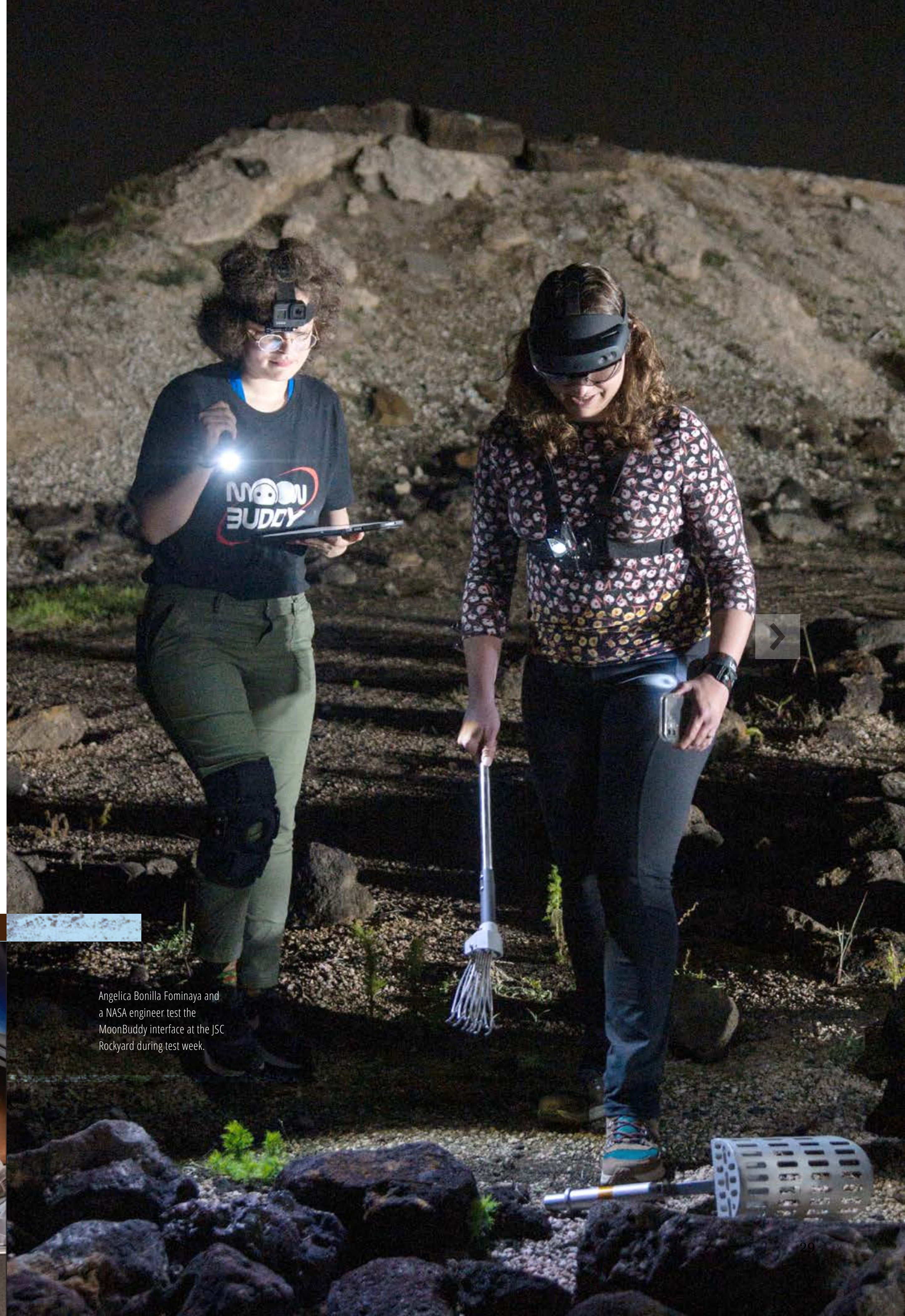
"I do think that the things we came up with in the challenge help build the foundation for the types of ideas that NASA will have when they're developing the interfaces for the new space suits," she said. "Maybe our interfaces won't be directly used in these missions, but if we find out that they use something similar to our work, we'll know that we helped this go further and that our ideas were the foundation for something bigger and better."

Importantly for Bonilla Fominaya, it made her realize she could achieve her childhood dream.

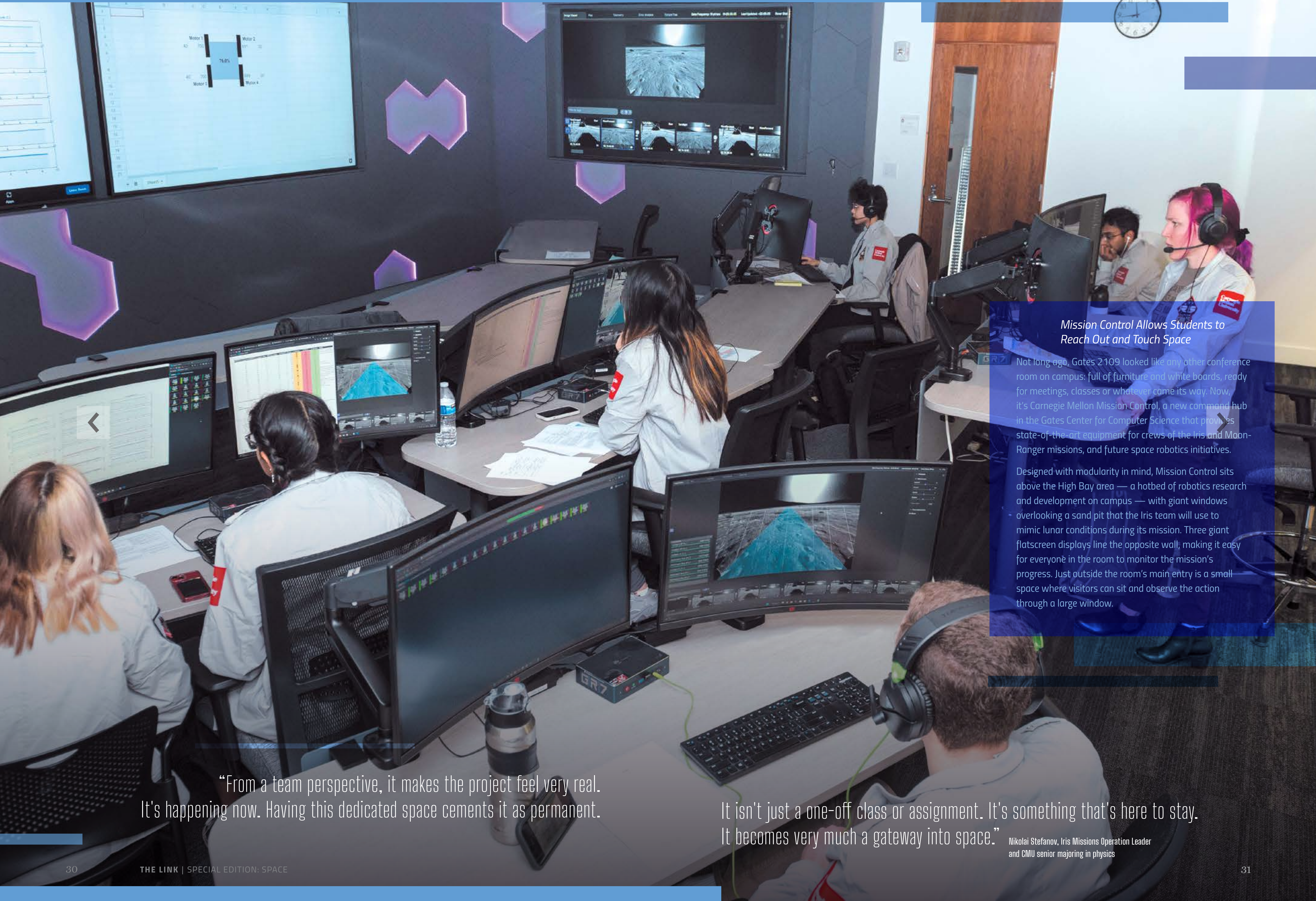
"It was such an educational experience in teaching us that you don't have to be a rocket scientist to work at NASA," she said. "You can do things at NASA as artists, designers and engineers working on user-interface design. There are real jobs at NASA for this kind of stuff."

"It ended up definitely being the most difficult and amazing experience I've had in my college career."

Students on the MoonBuddy Team: (Top Row) Rong Kang Chew, Alexandra Slabakis, Joyce (Yunyi) Zhang, Matthew Komar (Bottom Row) Anita (Ninying) Sun, Angelica Bonilla Fominaya, Jeremia Lo



Angelica Bonilla Fominaya and a NASA engineer test the MoonBuddy interface at the JSC Rockyard during test week.



Mission Control Allows Students to Reach Out and Touch Space

Not long ago, Gates 2109 looked like any other conference room on campus: full of furniture and white boards, ready for meetings, classes or whatever came its way. Now, it's Carnegie Mellon Mission Control, a new command hub in the Gates Center for Computer Science that provides state-of-the-art equipment for crews of the Iris and Moon-Ranger missions, and future space robotics initiatives.

Designed with modularity in mind, Mission Control sits above the High Bay area — a hotbed of robotics research and development on campus — with giant windows overlooking a sand pit that the Iris team will use to mimic lunar conditions during its mission. Three giant flatscreen displays line the opposite wall, making it easy for everyone in the room to monitor the mission's progress. Just outside the room's main entry is a small space where visitors can sit and observe the action through a large window.

"From a team perspective, it makes the project feel very real. It's happening now. Having this dedicated space cements it as permanent. It isn't just a one-off class or assignment. It's something that's here to stay. It becomes very much a gateway into space." Nikolai Stefanov, Iris Missions Operation Leader and CMU senior majoring in physics

Hexagonal acoustic tiles line the walls, providing both sound-dampening practicality and a little shout out to the Iris project.

"The hexagonal pattern is reminiscent of the molecular structure of carbon fiber — one of the reasons Iris will be able to get to space, as it allowed us to construct a durable chassis and wheels that weigh very little," said Iris Missions Operations Leader **Nikolai Stefanov**, a senior majoring in physics. "That's basically a carbon ring right there," he said, pointing to the paneling.

Within the control center, operator workstations give crew members space to plan and direct the movements of the rovers, monitor their data and images and communicate with them and each other. Crew members will also see telemetry, localization data and Fault List Evaluator for Ultimate Response (FLEUR) readouts at the workstations. A flight director will oversee all the action from the back of the room — against the windows looking into the High Bay — perfectly positioned to constantly see what's happening.

The space also contains a separate data room, with servers powering the main control room and a VPN connection to the landing companies that will relay communications from CMU to the lunar rovers. In the case of Iris, that's Astrobotic; for MoonRanger, NASA's Commercial Lunar Payload Services program.

William "Red" Whittaker, who heads the university's Field Robotics Center and plays a huge role in upcoming lunar initiatives, says this space is vital to mission success.

"There's the sense that technology makes or breaks the mission. And, of course, it matters to get that right. But it pales in comparison to all the eventualities and contingencies that occur during the mission," Whittaker said. "If something goes wrong, you have such a short time to address it, patch it and get into action. The only way to do that is to have your team co-located and you need a great facility that technically works in such a way that communications are impeccable and everybody has the same information."

Carnegie Mellon Mission Control also represents an important milestone for students working on space robotics — and who may have been dreaming about space exploration their entire lives.

"From a team perspective, it makes the project feel very real," Stefanov said. "It's happening now. Having this dedicated space cements it as permanent. It isn't just a one-off class or assignment. It's something that's here to stay. It becomes very much a gateway into space.

"Kids dreamed of becoming astronauts one day," he continued. "Well, this is a way you get to touch space like never before."

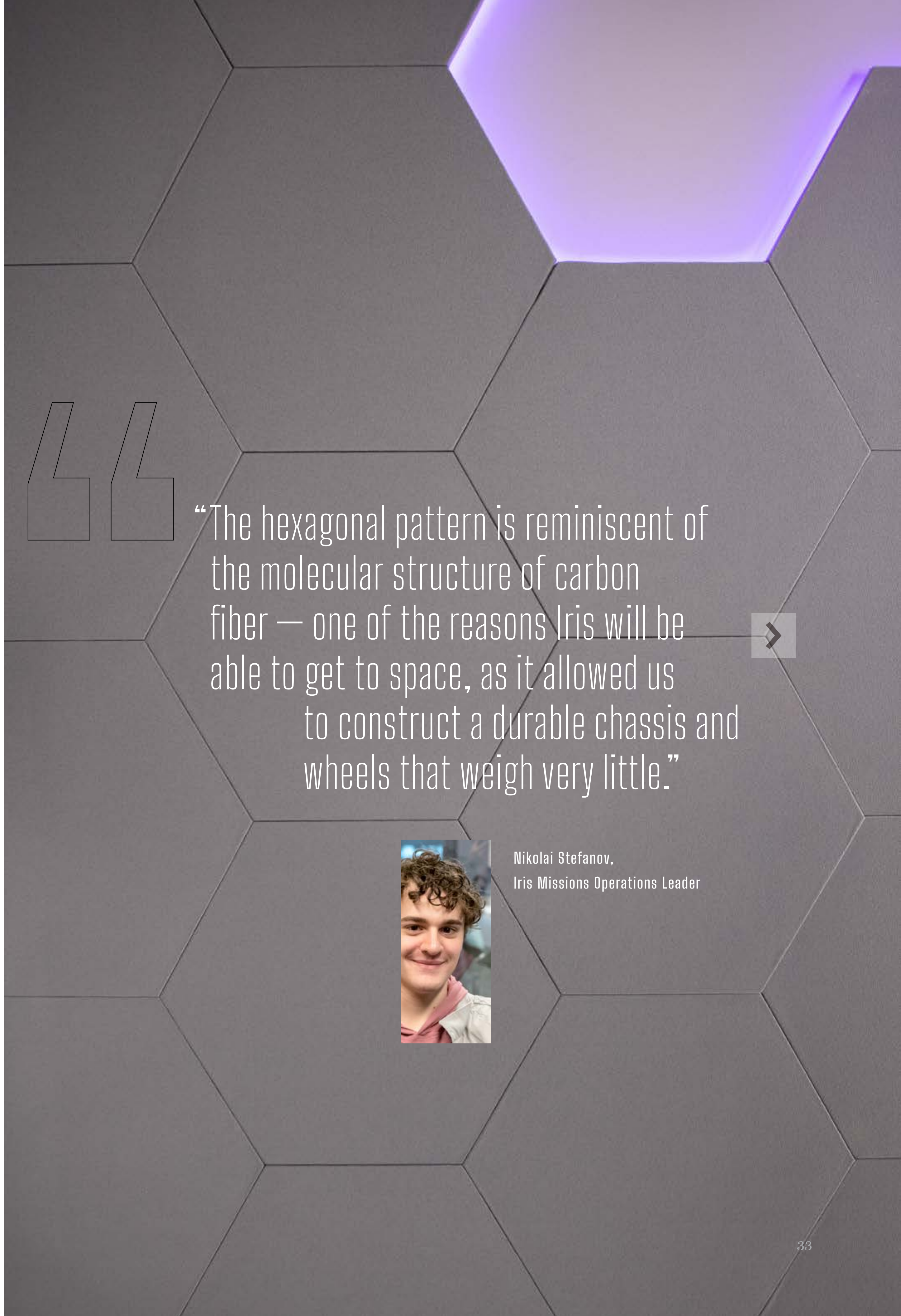
CMU, JPL Work to Ensure One Plus One Always Equals Two

Like Angelica and Nikolai, **Rashmi Vinayak** always found herself fascinated by space. But her research in coding theory never crossed paths with space exploration. Until now.

Vinayak, an assistant professor in the Computer Science Department, studies resource-efficient ways to make computer systems more robust and resilient. Her work has largely focused on how to accomplish this in data storage systems, or data center applications. But a fortuitous meeting led to its possible application in space.

Rashmi Vinayak, assistant professor in the Computer Science Department

"I was describing to some folks from Google that we were looking into protecting



"The hexagonal pattern is reminiscent of the molecular structure of carbon fiber — one of the reasons Iris will be able to get to space, as it allowed us to construct a durable chassis and wheels that weigh very little."

Nikolai Stefanov,
Iris Missions Operations Leader

computation using coding theory tools. And it turned out that a partner of one of the Googlers works at NASA's Jet Propulsion Laboratory," Vinayak said. "We got in touch and started having regular meetings."

Vinayak and JPL are trying to minimize computation errors in space caused by cosmic radiation. The problem isn't a new one. As altitude increases, cosmic radiation — the high-energy charged particles produced in space — interacts with the silicon used to perform computation and generates errors, known as soft errors, transient errors or bit flips (all different names for the same thing). Vinayak gives the example of sending a simple computation like one plus one.

"Most of the time, you get two," she said. "But sometimes you don't. How can we do reliable computation on such an erroneous substrate?"

To eliminate the likelihood of the "not two" answer, computing systems in space (or in national labs sitting at high altitudes or even air traffic control systems) have two options: performing the computation multiple times and taking the majority answer — a sort of computational "best out of three" — or doing what is called radiation hardening, encasing the actual hardware in materials that protect it from radiation. The former is expensive and data intensive. The latter is expensive and bulky. Neither is a good option for computation in space, as more and more accelerators such as graphic processing units are becoming popular in the field for machine learning tasks.

Enter Vinayak's coding theory solution.

"Coding theory revolutionized digital communication decades ago by enabling us to add redundancy in a resource-efficient manner that does not require replication that could increase overhead by 200% or 300%. That's too much in any system," she said. "Coding theory enables us to add a fractional amount of overhead, for example, 10% or 20%, but still provide the same amount or even more fault tolerance than one can do by replication."

It's all incredibly math-dense, but Vinayak gives an overly simplified example from data storage to illustrate using integers A and B. One way to protect them is to store multiple copies — A, A and B, B — on different devices, so if one fails there's still another copy. With two copies of the data, you need twice the resources to store it.

"Instead, think about this other approach," she said. "I have A and B, but instead of having two copies of them, I store A, B and A+B. These are all stored on different devices. Let's say A is lost. Now I have B and A+B, so I can get A back with only 50% more overhead."

In technical terms, A+B would be known as a parity, a mathematical function of the original data that helps protect it. And while her example uses data storage, it's also applicable to computation in a more nuanced way.

"You perform your original computation on the original data units, as well as on this function of the original data. Then the output of the latter can help you recover any of the original computation if it's lost or detect if there's an error," Vinayak said.

> "It's the visceral excitement of space. It's pushing the frontier of human knowledge. There's so much unknown about outer space, and getting knowledge about space can help us know more about ourselves and how the universe came into being. I'm super excited about this project."
>
> Rashmi Vinayak

While still in its nascent stages, the JPL collaboration could influence how calculations are performed in future space missions and allow more of those calculations to happen reliably in space instead of sending all the data back to Earth. Right now, JPL is testing Vinayak's coding theory approach under different radiation conditions in the lab to see how it responds.

Vinayak can't hide her joy at being involved in space research.

"Even in childhood, I was fascinated by space," she said with a grin. "It's the visceral excitement of space. It's pushing the frontier of human knowledge. There's so much unknown about outer space and getting knowledge about space can help us know more about ourselves and how the universe came into being. I'm super excited about this project."

Space Filter

DEVELOPMENT OF SMART SATELLITE AIMS TO TAME THE DATA DUMP

NIKI KAPSAMBELIS

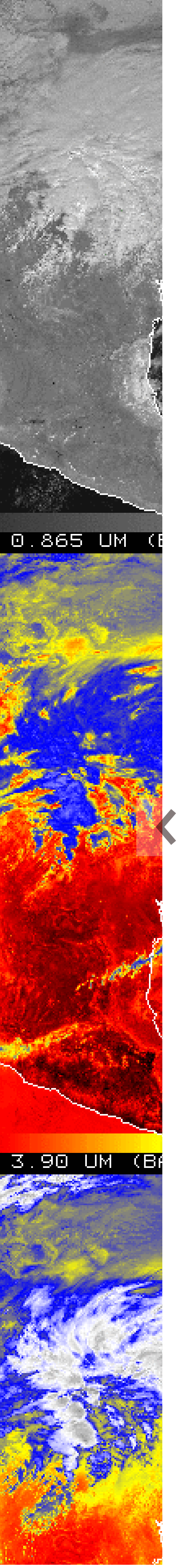
Imagine riding a train across the United States, recording everything you see from the window in precise detail. *Every few hours, the train stops for five minutes, and you have only that amount of time to share what you've captured with a person waiting at the station before the train takes off again.*

Now imagine circling Earth, collecting even more information, but you still only have the same five minutes to share it — and no way to sort through what's relevant. How useful is the data likely to be?

That is the conundrum faced by a wide swath of government entities and private corporations using satellites to collect images. Thousands of satellites orbit Earth, according to the United Nations' Outer Space Objects Index. Not all are active, but those that are take high resolution video 24 hours a day, seven days a week.

Currently, they downlink those giant volumes of raw data to ground stations on Earth every few hours, dumping whatever information they can in a five-minute span.

"That creates this huge bottleneck," explained Zac Manchester, assistant professor at the Robotics Institute.



"We want to make the satellites able to process their own data in orbit, and a lot more autonomous in general." Zac Manchester, Assistant Professor, Robotics Institute

A decade's worth of investment in infrastructure has resulted in better radios and more ground stations, but little headway has been made to address the bottleneck, because new satellites are launched too frequently to allow the infrastructure to catch up to them.

"It's kind of a losing game," said Manchester. "You can do incrementally better, but even after a decade's worth of investment, you've probably only got a 10% improvement. It's a tough, expensive thing to do."

BUILDING SMARTER SOLUTIONS

A team from Carnegie Mellon aims to make satellites smarter, curating downloads to make them more relevant to the end user. The project, backed by a five-year, $7 million grant from the National Science Foundation, is housed at the Robert Mehrabian Collaborative Innovation Center. Manchester is part of the team, which is led by principal investigator Brandon Lucia of the Electrical and Computer Engineering Department.

"We want to make the satellites able to process their own data in orbit, and a lot more autonomous in general," Manchester said. As an example, satellites take a lot of photos of clouds, wasting limited bandwidth. A person on the ground must then manually manage that data, adding to inefficiency.

Smart satellites would have sensors that collect data from across the electromagnetic spectrum, which is valuable for seeing features of the Earth or its atmosphere, explained Lucia. For example, multispectral bands can show short- and long-term weather patterns, or the presence or absence of moisture, which is important for agriculture.

Sensors can also help optimize smart cities by showing details such as traffic congestion, he noted.

But because the volume of data is so massive — on the order of about a terabyte per orbit — sorting through what's useful becomes critical. If machine learning could triage the data on the satellite, it could work smarter within its limited bandwidth and download only what is useful, instead of leaving that task to someone on the ground: "Now you can squeeze a lot more out of the bandwidth that you've got," Manchester said.

Brandon Lucia

Gauri Joshi

Swarun Kumar

Zac Manchester

Vyas Sekar

Smart Satellite Research Team

Headquartered in the Department of Electrical and Computer Engineering (ECE), satellite research is a collaborative effort involving faculty with expertise in design, wireless communications, networking, security and AI.

The research is funded by a five-year, $7 million grant from the National Science Foundation. Team leaders include:

- **BRANDON LUCIA** (principal investigator), Sathaye Family Foundation Career Development Professor of Electrical and Computer Engineering
- **GAURI JOSHI**, associate professor, Electrical and Computer Engineering
- **SWARUN KUMAR**, associate professor, Electrical and Computer Engineering
- **ZAC MANCHESTER**, assistant professor, The Robotics Institute
- **VYAS SEKAR**, Tan Family Professor of Electrical and Computer Engineering

The group has collaborated on several space launches prior to winning NSF funding. During the five-year cycle of that grant, they hope to create enough basic research, including additional launches, to enable future nanosatellite projects.

"We are the only NSF center that's working on this topic, and we're a unique effort, because we have a really diverse team," Lucia said.

COUNTING DOWN TO LAUNCH

Manchester's lab works on guidance navigation and control, or GNC in aerospace parlance. The project plans to launch a baseball-sized satellite known as PocketQube in April 2023 to test algorithms developed by the team to adjust its attitude, or orientation, in space.

"If we pull it off, it will be the smallest spacecraft ever with full attitude control," said Manchester.

Currently, to point the satellite in the direction it needs to travel, someone on the ground needs to control it. One method uses a motor, which can be heavy and difficult to scale to smaller satellites. In addition, motors can wear out. As an alternative, Manchester's lab has developed algorithms that navigate using electromagnetic coils in the solar panels on the satellite's face, which push on the Earth's magnetic field — similar to the way a compass needle works.

Though the underlying concept has been well established, the new algorithms are designed to be more accurate in pointing the satellite in the desired direction: "You basically use the Earth as the other half of your motor," Manchester explained.

If successful, **PocketQube** could provide a significant advantage in developing low cost, highly functional small satellites that could deploy in swarms. Drawing on inspiration from schooling fish or flocking birds, satellite swarms eventually will talk to each other with radio signals, figuring out how to get to where they need to go, Manchester said. Swarms offer better distribution and lower costs than larger satellites, and losing one is less problematic than losing a single large satellite. The launch is part of the center's five-year plan to conduct basic research and space launches to enable future missions, said Lucia.

Ultimately, these swarm satellites could identify signs of a wildfire before it rages out of control, allowing local firefighters to respond more quickly. Monitoring wide swaths of ocean would also allow for faster searches of plane or boat wreckages.

"Our vision is a minute turnaround time," said Lucia.

PocketQube: small, less expensive and smarter swarm satellites that communicate with one another for navigation

> " If we pull it off, it will be the smallest spacecraft ever with full attitude control."

Zac Manchester, Assistant Professor, Robotics Institute

> " I think humanity's endeavor into space is one of the greatest journeys of mankind, and it's exciting to be on that journey."

Jacob Willis,
Ph.D. candidate in the Robotics Institute

WIDENING ACCESS THROUGH COLLABORATION

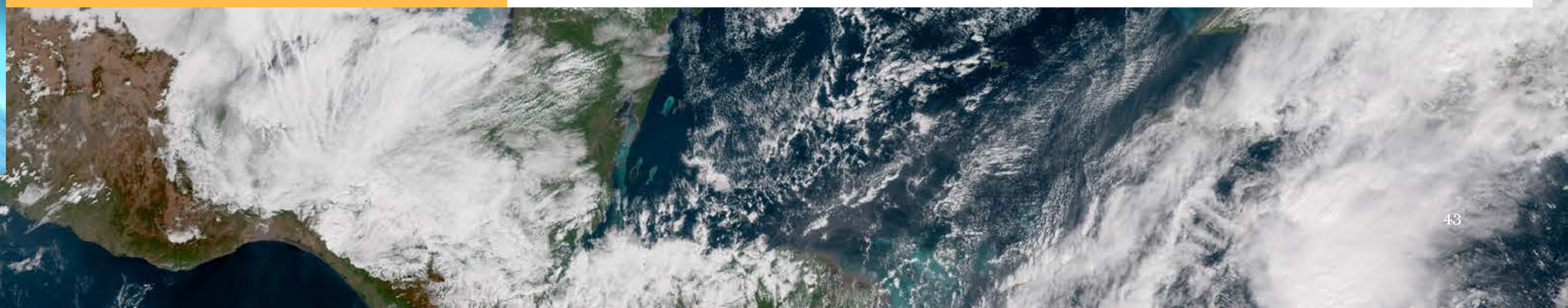
Through a partnership with Universidade do Minho and Instituto Superior Técnico in Portugal, Manchester is also using PocketQubes to collaborate on a project designed to widen access to space exploration. Known as Prometheus, its goal is to provide a complete open-source satellite — including hardware designs, software and control algorithms — that can be built by students for under $1,000. The partnership will steer the Prometheus project from development through licensure, certification and launch, giving students hands-on learning through each step of that process.

Jacob Willis, a second-year doctoral student in the Robotics Institute, oversees a team of four undergraduates, two master's degree candidates and another doctoral student in Manchester's lab. He stressed the importance of their collaboration in getting Prometheus and other satellites into space.

"The students I'm working with are fantastic. This project, and really any spacecraft development project, is a team effort," he said. Lucia agreed, noting the influence that different disciplines within Carnegie Mellon have on each other: "All our efforts are amplified by others across departments," Lucia said.

For Willis, who began working on satellites as an undergraduate, the unsolved problems of spacecraft control are particularly intriguing.

"I think humanity's endeavor into space is one of the greatest journeys of mankind, and it's exciting to be on that journey," he said. "We're breaking off the surface of the Earth and exploring new domains." ■



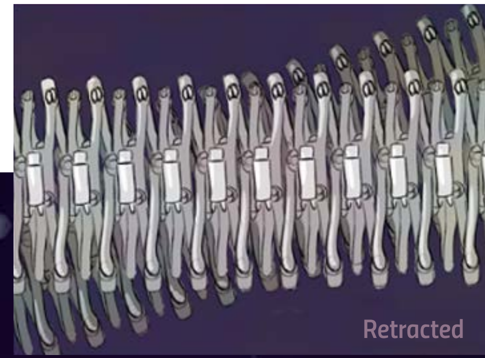
EXPEDITION 46 COMMANDER SCOTT KELLY ON A DEC. 21, 2015 SPACEWALK

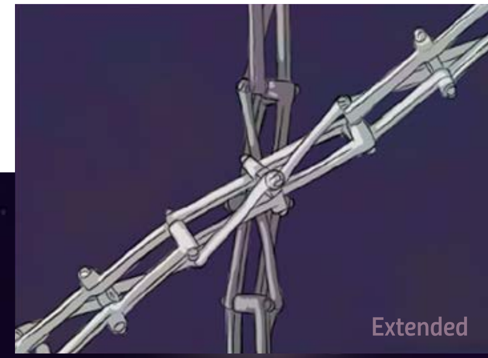
Simulating Gravity

CHRIS QUIRK

ON THE MORNING OF MARCH 2, 2016, the Soyuz spacecraft carrying Commander Scott Kelly and cosmonaut Mikhail Kornienko descended from the International Space Station and bumped down on the Eurasian Steppes of central Kazakhstan. Kelly, who had been orbiting Earth for 340 days in the zero-gravity environment of the space station, was severely weakened after almost a year of floating freely in weightless conditions. The ground crew gingerly lifted the normally strapping Kelly out of the capsule and carried him to the nearby medical tent for testing.

FLEX STRUCTURES FOR SPACE WOULD BE RETRACTED UPON LAUNCH THEN EXTEND AND LOCK INTO PLACE UPON DEPLOYMENT.





The central problem in simulating gravity in space by spinning is that humans begin to experience motion sickness at speeds of just two or three revolutions per minute. "That is really slow," said Manchester. "In order to get near Earth's gravity at around a 1.3 rpm range, you need a structure that is about a kilometer in length."

Assembling a kilometer-long tower piece-by-piece in space would be a difficult enough task, but Manchester and Lipton plan to pack it into a single rocket.

"The classic way to do something like this is to fold it all up, like origami, into a really small space inside a rocket, then some-how deploy it," Manchester said. "Right now, if you think about expansion ratios, the limits on what you can take up there and unfurl are around five or 10 times the original size. To get to a kilometer, you need to start with something about 10 meters in length and have an expansion ratio of 100-to-1."

To achieve such an extreme expansion ratio, Manchester and Lipton are combining scissor joints — similar to what you would see on a pair of expanding tongs — with a technique Lipton calls handed shearing auxetics, a slinky-like form that twists as it unscrews and expands in length. "At one scale, you've got a scissor mechanism, and then that second structure that gives you another property," Lipton said. "By combining the two into a hierarchical metamaterial, each operating on its own scale, we can get a much larger expansion ratio."

The materials and hinging apparatus on the space structure will be critical to the success of the project. Manchester and

Lipton are scouring the archives to find new or overlooked ideas for connecting the hundreds of thousands of pieces that will constitute the final structure. "It's a deep literature search on all the different latching technologies out there and how we could apply them in a space context," Lipton said.

As if these hurdles weren't enough, the plan is to have a pod on each end of the kilometer-long arm large enough to house an astronaut. Naturally, there would be quite a bit of flex in the structure as it opens, and once it extends. As the structure deploys to its full length in space, with hundreds of thousands of joints opening and struts locking into place, plenty of things could go wrong. Manchester's idea is to use the natural flex in the elongated system to help ease the parts into order to avoid jamming.

"You've got to manufacture this thing, and nothing is perfect, so you are going to have these little issues all over the place," he said. "At the end of the day, it's got to have one degree of freedom. All these pieces have to come together in one specific way. But with enough flex and wiggle room, things will sort of nudge into place, the alignment issues should just be noise."

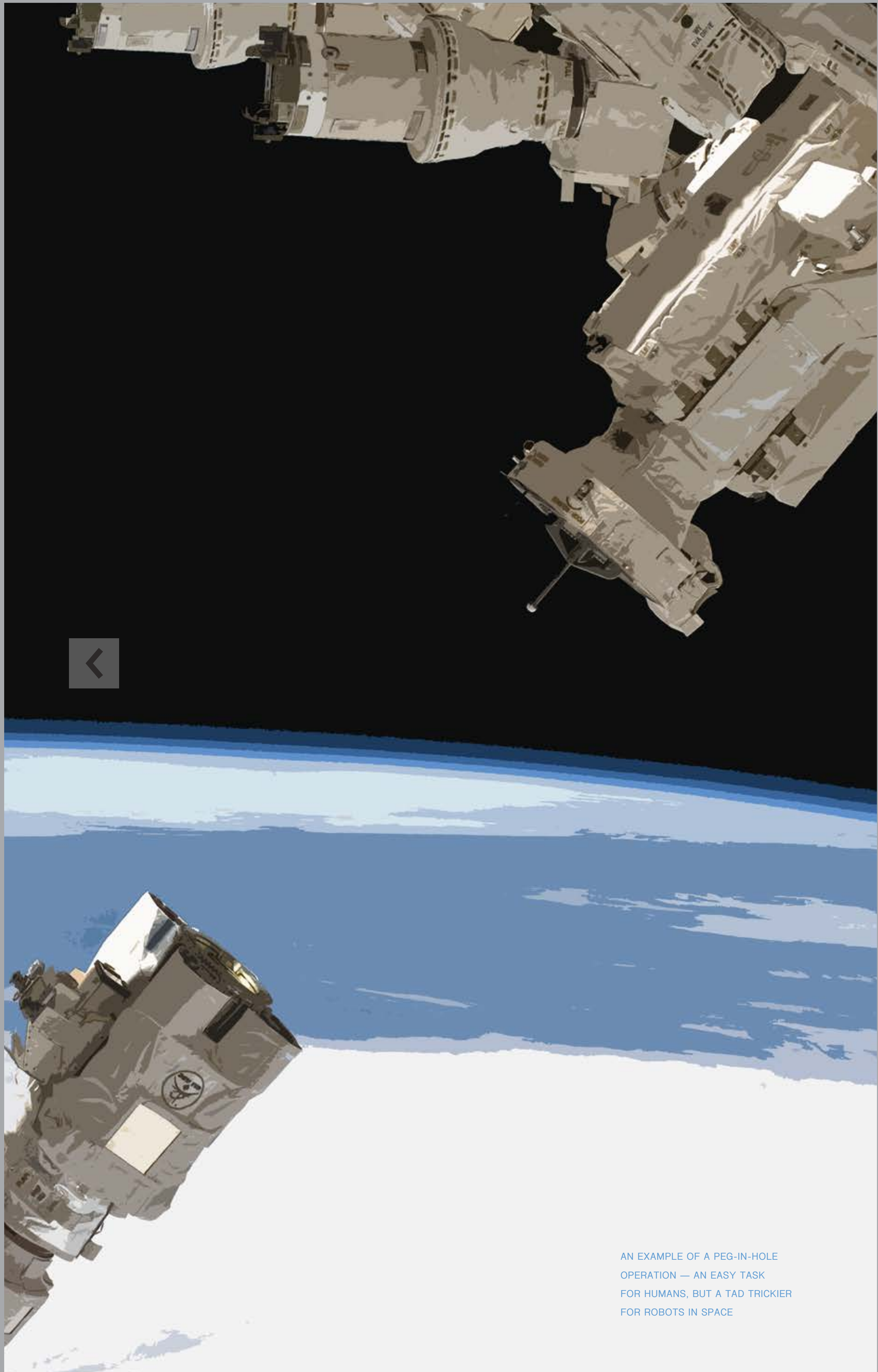
At present, Manchester and Lipton are proceeding on parallel tracks while exchanging information frequently. The two have known each other since their undergraduate days at Cornell, where they also both earned their doctorates. Lipton is handling the mechanical and materials side of the project and Manchester is working on the computer modeling. "The math is super gnarly," said Manchester. "You've got so many pieces, simulating several hundred thousand links. It's just huge. So, what we do is, where feasible, use fewer pieces, average out all those links, and simulate expanding in chunks. Then we look at the fully expanded structure to see vibration, flexibility and all that stuff."

Despite the complexity of the project, the pair has made rapid progress. Lipton estimates they have already achieved about a 40-to-1 expansion ratio in their design. On the agenda at some point is a trip on a zero-gravity, parabolic airliner flight — popularly known as a vomit comet — to see how the apparatus responds in space-like conditions. "We'll be able to check it in various states of deployment and do local tests," Lipton said. "We'll also have fully deployed sections and be able to do regional tests and see how they deal with the acceleration." ■

(RIGHT) JAMES BURGESS (HNZ 2017), A CLINICAL NEUROSURGEON AND MASTER OF MEDICAL MANAGEMENT, SUBMITTED THIS IMAGE FROM INSIDE THE NASA 'VOMIT-COMET' WHILE WORKING ON A RESEARCH PROJECT STUDYING BLEEDING IN LOW GRAVITY WITH (LEFT) KATE MEACHAM (E 2001), PH.D. AND RESEARCH FACULTY IN THE GEREAU LAB AT WASHINGTON UNIVERSITY, AND UNIDENTIFIED RESEARCHER (CENTER).

"The vomit comet is a bucket list thing Jeff and I have, but we would squeeze a lot of experiments into those short, zero-gravity descents."

ZACHARY MANCHESTER



AN EXAMPLE OF A PEG-IN-HOLE OPERATION — AN EASY TASK FOR HUMANS, BUT A TAD TRICKIER FOR ROBOTS IN SPACE

A NEW KIND OF SPACE RACE

ROBOTICS INSTITUTE RESEARCHERS PARTNER WITH ACADEMIA, INDUSTRY TO REDUCE SPACE "JUNK"

by KAYLA PAPAKIE

Think of the last time you put a key into a keyhole to unlock the door to your home or plugged a cord into an outlet to power up an electronic device. There's a good chance you do small tasks like this every day, quickly and deftly, without even realizing you're doing them.

Now imagine you're in space.

“Everything is spinning around at its own speed. You're trying to put the key into your lock, but your house is moving, and you're moving too,” said Howie Choset, the Kavcic-Moura Professor of Computer Science in the Robotics Institute.

These processes, known as peg-in-hole operations, are one of the many tasks essential to On-Orbit Servicing, Assembly and Manufacturing (OSAM), an emerging field where tools and technology are deployed to extend the lifespan of satellites. Peg-in-hole operations like unlocking a door or plugging in a phone charger are simple tasks we humans take for granted, but they aren't so easy for robots.

"PEOPLE TEND TO REALLY UNDERESTIMATE JUST HOW DIFFICULT THESE TASKS ARE. THEY REQUIRE A LOT OF PRECISION AND DEXTERITY"

HOWIE CHOSET, Professor in the Robotics Institute

Choset and his team in the Biorobotics Lab study OSAM to explore ways in which robots can be put to use in space, particularly, how they can help to extend the lives of satellites.

Of the more than 6,300 satellites orbiting Earth, only half remain functional. Whether they've run out of fuel, malfunctioned or simply reached their intended lifespan, the disabled machinery is either guided to crash back into Earth's atmosphere and denigrates upon re-entry or is pushed to an outer orbit – a satellite graveyard, of sorts – more than 200 miles away from any working spacecraft. These graveyards have come to be known as junk orbits, where more than 27,000 pieces of human-made space debris now float above the Earth.

To break this "launch once, use once" paradigm, Choset, along with Matt Travers, co-director of the Biorobotics Lab, and Carmel Majidi, a professor in CMU's College of Engineering, will lead a consortium as part of the Space University Research Initiative (SURI) out of the Air Force Research Laboratory and the Air Force Office of Scientific Research.

"If you could launch one rocket and have it serve multiple missions with that single launch, that is an absolute game changer in terms of efficiency and economy," said Travers.

According to Choset, getting to that point is a big, multifaceted challenge. "A lot of different things have to come together to make this work," he said.

Logistically, the team must consider how to build the robots before they deploy, how to launch them into space and how to control them once in orbit. Their research builds on previous work conducted by Choset and Travers with aerospace defense company Northrop Grumman that explored robotics and artificial intelligence for the company's Mission Extension Vehicles.

"We're hitting a point where there is commercial viability," said Choset. "There's money to be made here. Think of all those broken satellites. That's trillions of dollars of hardware floating around."

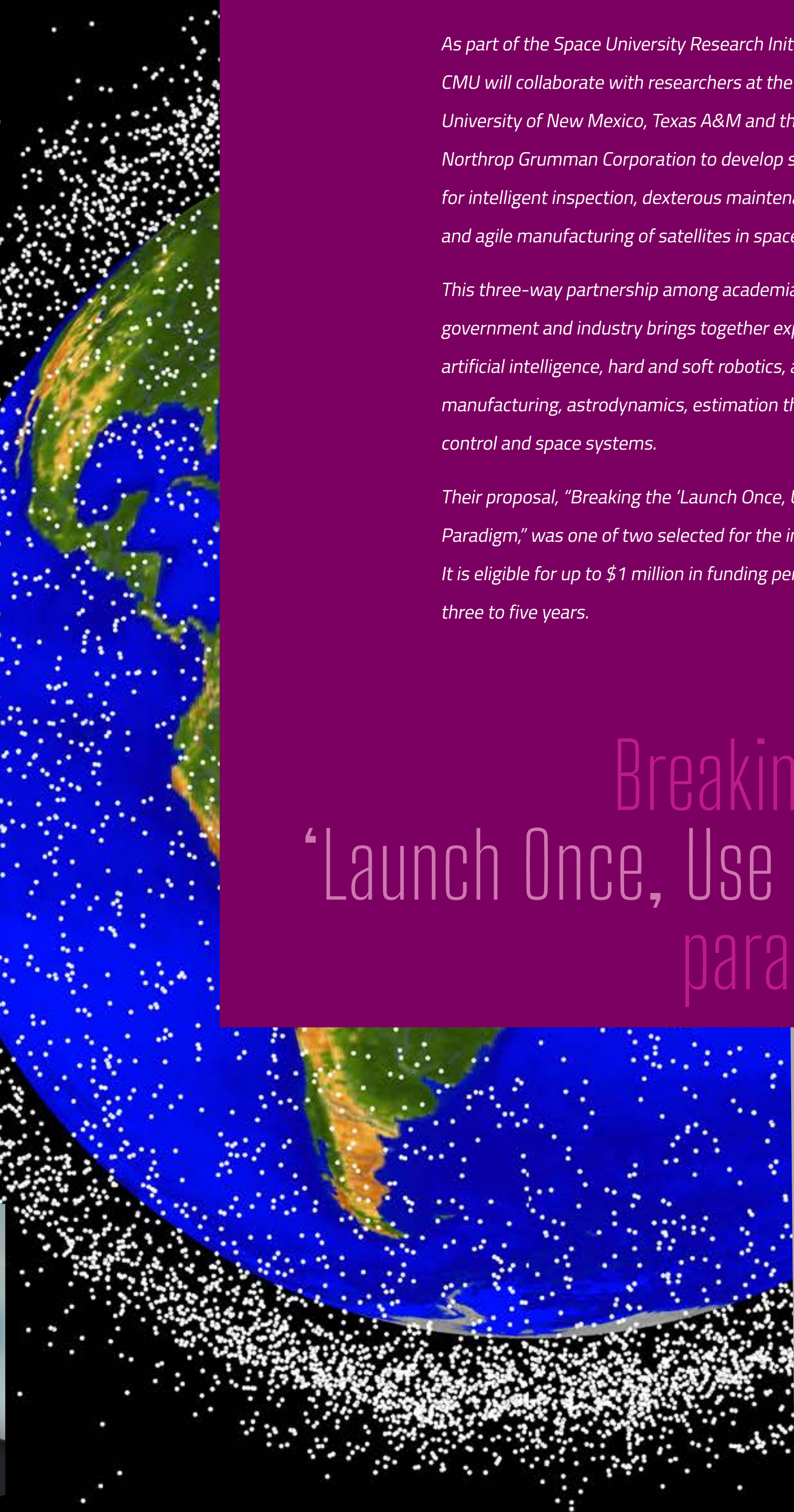
There are a number of ways in which this technology could help to prolong a satellite's usefulness.

"A satellite's mission could dramatically change or there could be slight modifications where adding a sensor or adding a new rocket boost could completely renew its life cycle," Travers said. "Bringing these capabilities to space makes a ton of sense."

Howie Choset
Professor in
Robotics Institute

Matt Travers
Co-director
Biorobotics Lab

Carmel Majidi
Professor in
Mechanical Engineering

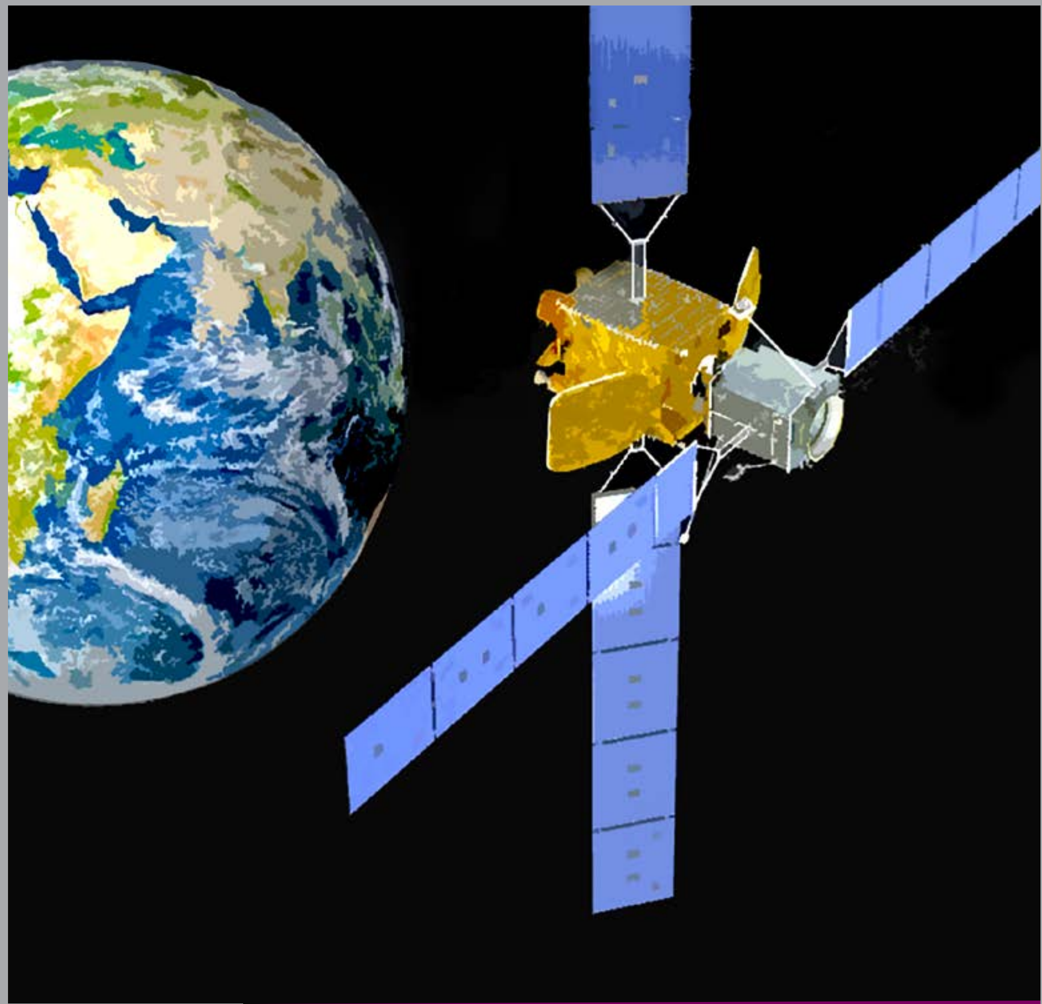


As part of the Space University Research Initiative, CMU will collaborate with researchers at the University of New Mexico, Texas A&M and the Northrop Grumman Corporation to develop systems for intelligent inspection, dexterous maintenance and agile manufacturing of satellites in space.

This three-way partnership among academia, government and industry brings together expertise in artificial intelligence, hard and soft robotics, additive manufacturing, astrodynamics, estimation theory, control and space systems.

Their proposal, "Breaking the 'Launch Once, Use Once' Paradigm," was one of two selected for the initiative. It is eligible for up to $1 million in funding per year, for three to five years.

Breaking the 'Launch Once, Use Once' paradigm.

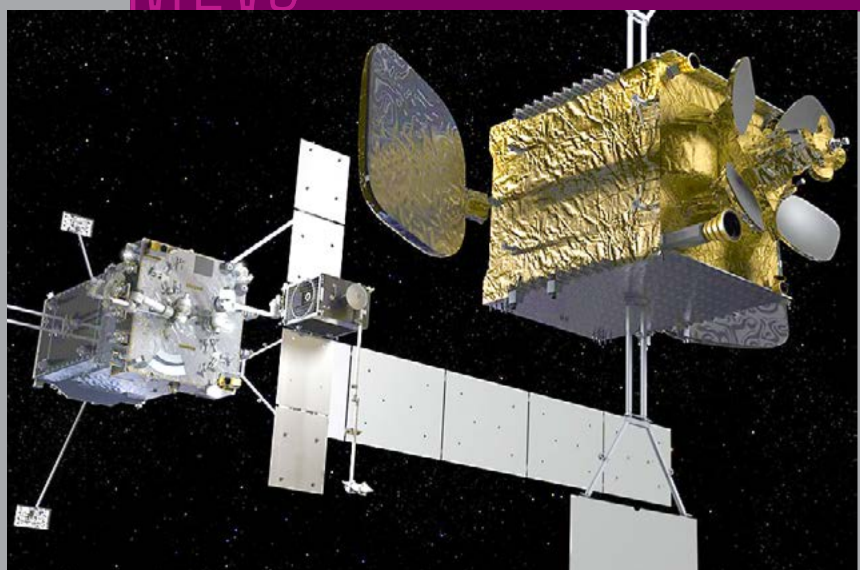


Mission Extension Vehicles

Northrop Grumman has had early success with its Mission Extension Vehicles, the first of which docked on a client satellite in 2020. MEVs use their own thrusters and fuel supply to extend the satellite's lifespan. Once the satellite no longer needs servicing, the MEV can undock and move on to the next satellite in need. In 2021, the company's second MEV docked with an orbiting satellite.

CMU partnered with Northrop Grumman's subsidiary SpaceLogistics on this next generation of satellite life extension vehicles by assisting with vehicle dynamics in the company's Rendezvous, Proximity Operations and Docking Lab.

MEVs



A Northrop Grumman Mission Robotic Vehicle uses its robotic arm to service a satellite in this rendering.

In addition to extending the lives of satellites in orbit, potential exists to lower the overhead costs of manufacturing and launching satellites by making them compact enough to be robotically assembled in space. Currently, satellites are carefully designed to be folded up and placed into the cargo bay of a space shuttle. They then have to withstand the pressure of being launched. Then once they're in space, they unfold and deploy.

"A lot of effort goes into building that satellite just so it could survive launch," said Choset.

The Biorobotics Lab has a long history of building and deploying modular robots, and Choset believes this work, known as fixture-free manufacturing, can be transferred to satellites. The team is proposing modular satellites, with parts that can be packed up into small modules and then put together like Legos once in orbit.

At the root of the robotic servicing and assembling of satellites are fundamentals like control theory and robot manipulation.

"Building robots that can fuel satellites or build new ones is not enough. We have to control these robots," said Choset. "You can't just tell the robot to go straight, because it's floating around in space."

Control theory uses mathematics to predict and analyze system behavior, while robot manipulation refers to the ways in which a robot interacts with an object, like those ostensibly easy, but theoretically difficult peg-in-hole operations. These fundamental concepts present a framework for how to predict and guide robot movements as they complete tasks in space. However, these tasks could be complicated by anything from solar flares to gravity and momentum. What's more, a lag in communication from Earth to space further hinders such operations.

"That latency makes it very difficult to have a person on the ground with a joystick saying, 'a little to the right, a little to the left' because they'd make a move, and it takes a couple seconds for that message to get transmitted," Travers said. By the time that command reaches the robot in space, it would already be in a different position than it was when the message was sent.

Considering the many moving parts to this research, Choset believes that few places are more equipped to handle such a complex venture.

"CMU is at a tipping point where, if we coagulate the efforts across our programs, I think we could be a space center," said Choset. "There is an opportunity here for our university and our region to really have a coordinated impact in space." ■

"CMU IS AT A TIPPING POINT WHERE, IF WE COAGULATE THE EFFORTS ACROSS OUR PROGRAMS, I THINK WE COULD BE A SPACE CENTER. THERE IS AN OPPORTUNITY HERE FOR OUR UNIVERSITY AND OUR REGION TO REALLY HAVE A COORDINATED IMPACT IN SPACE."

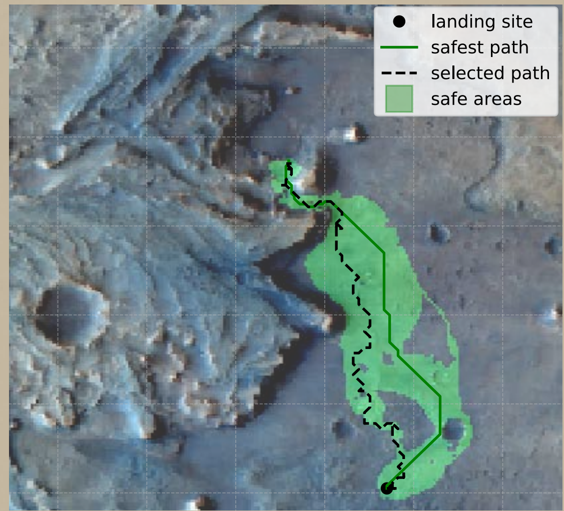
HOWIE CHOSET, the Kavcic-Moura Professor of Computer Science in the Robotics Institute

Automated Science *in* Space

CMU RESEARCHERS BALANCE RISK AND REWARD IN PLANETARY EXPLORATION

AARON AUPPERLEE

NASA's Mars rovers strive for groundbreaking scientific discoveries as they traverse the Martian landscape. At the same time, the crews operating the rovers do all they can to protect them and the billions of dollars behind the mission. This balance between risk and reward drives the decisions surrounding where the rovers go, the paths they take to get there and the science they uncover.



While considering a potential scientific destination, the rover must survey the landscape and plot the best path, assessing risks against other potential locations.

Researchers in the School of Computer Science's Robotics Institute (R.I.) have developed a new approach to balancing the risks and scientific value of sending planetary rovers into dangerous situations.

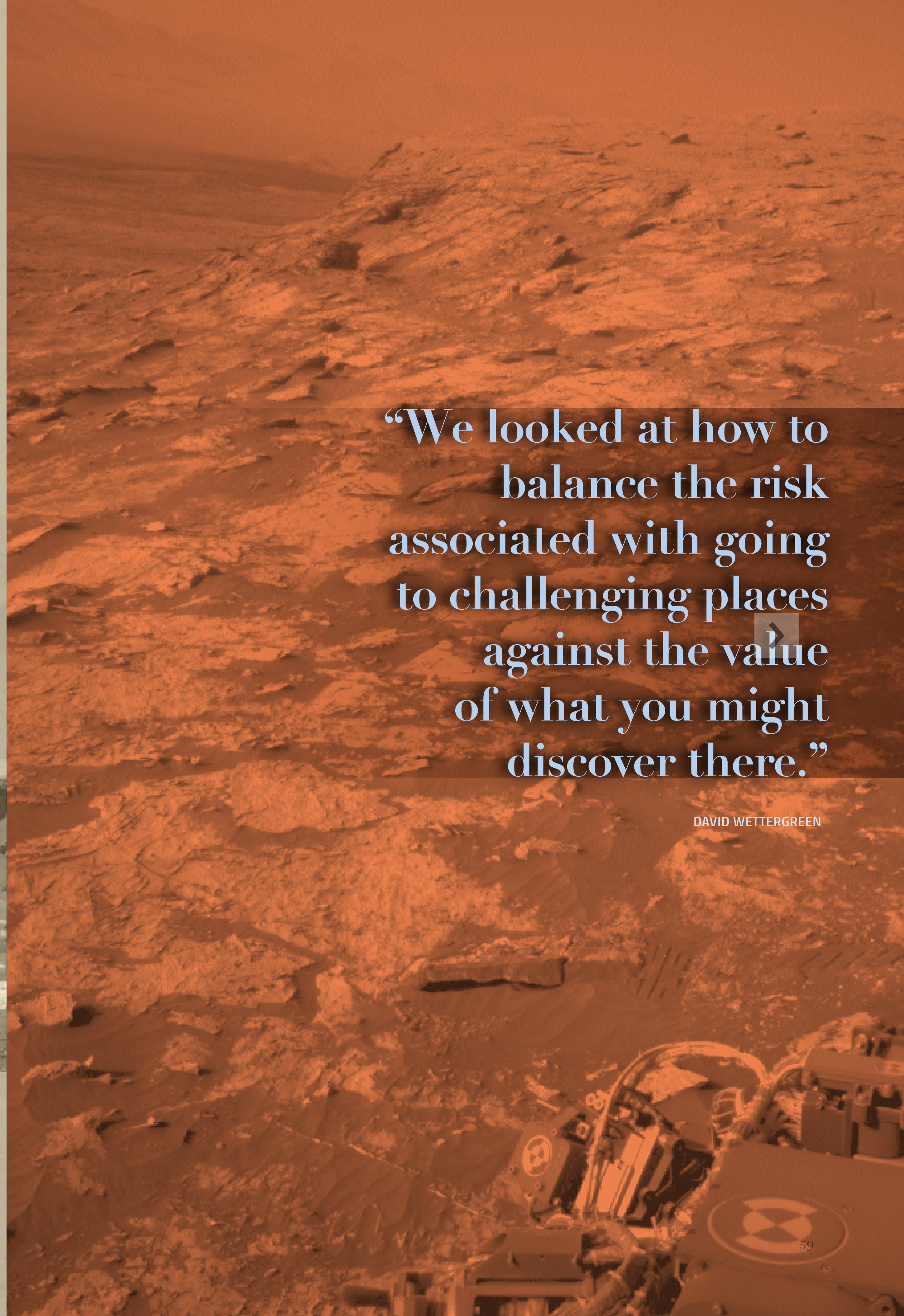
David Wettergreen, a research professor in the RI, and Alberto Candela, who earned his Ph.D. in robotics and is now a data scientist at NASA's Jet Propulsion Laboratory, presented their work, "An Approach to Science and Risk-Aware Planetary Rover Exploration," at the IEEE and RSJ International Conference on Intelligent Robots and Systems, October of 2022 in Kyoto, Japan.

"We looked at how to balance the risk associated with going to challenging places against the value of what you might discover there," said Wettergreen, who has worked on autonomous planetary exploration for decades at Carnegie Mellon University. "This is the next step in autonomous navigation and to producing more and better data to aid scientists."

For their approach, Wettergreen and Candela combined a model used to estimate science value with a model that estimates risk. Science value is estimated using the robot's confidence in its interpretation of the mineral composition of rocks. If the robot believes it has identified rocks

David Wettergreen
Professor in Robotics Institute

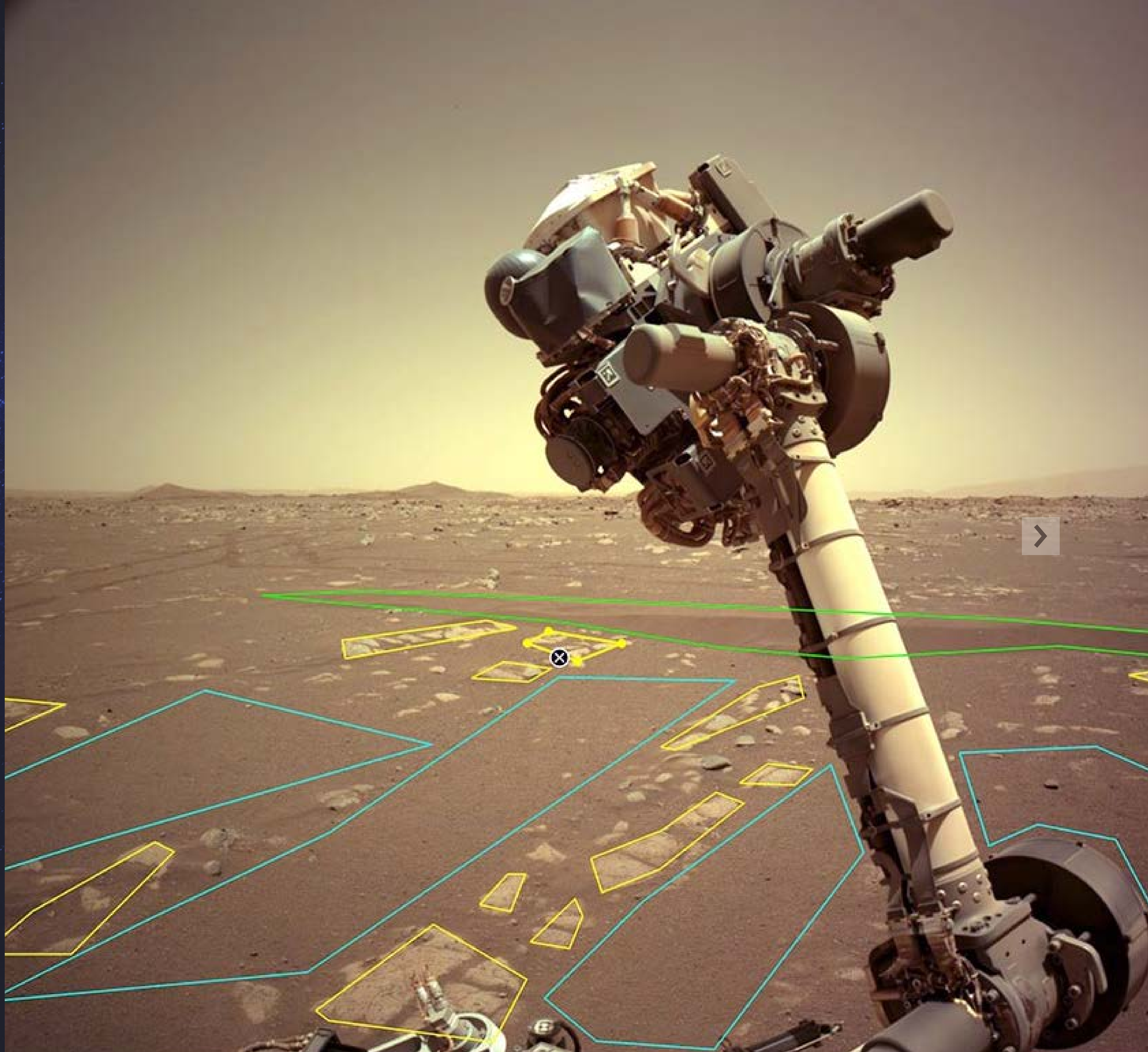
Alberto Candela (CS 2021)
Data Scientist at NASA's Jet Propulsion Laboratory



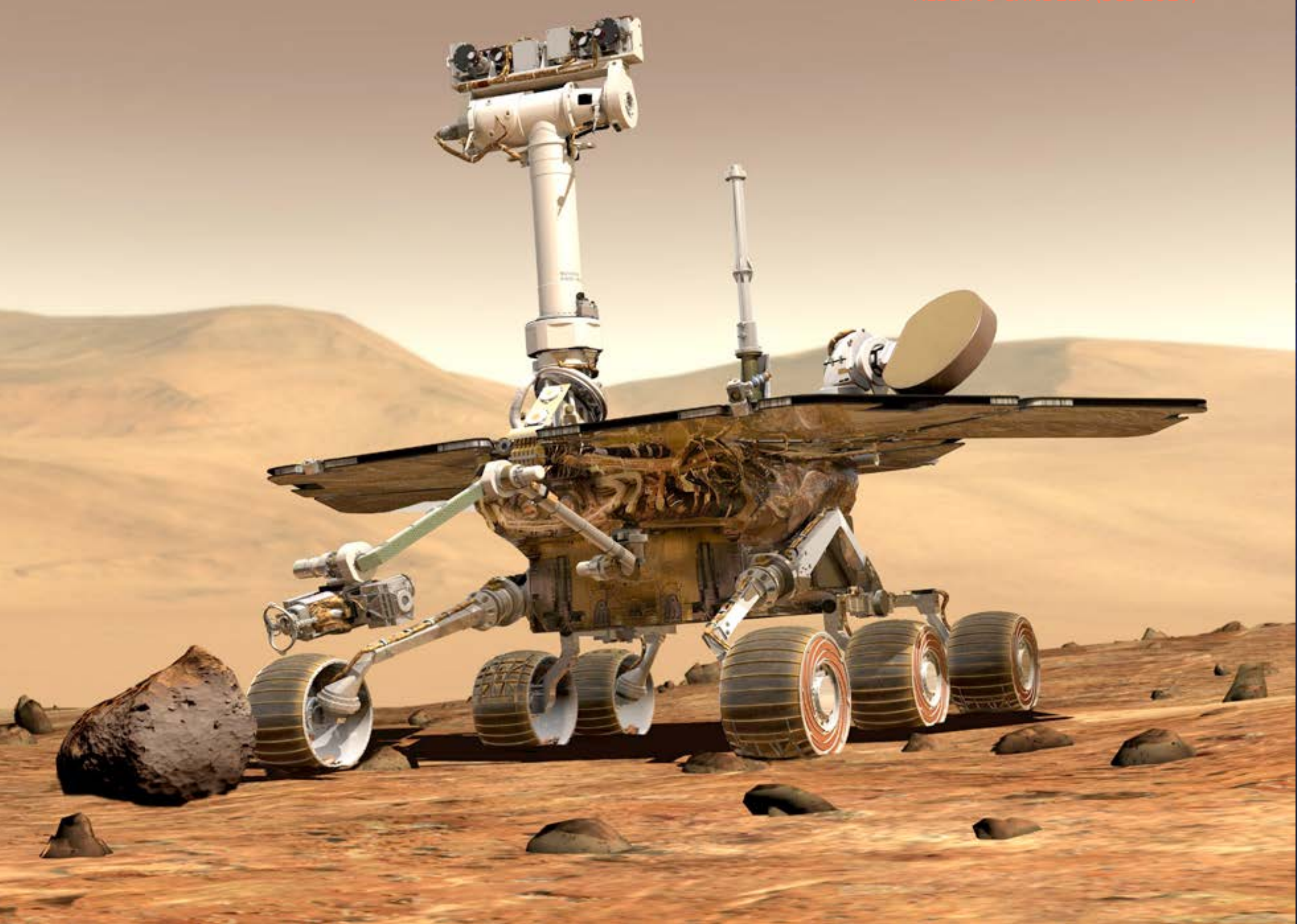
"We looked at how to balance the risk associated with going to challenging places against the value of what you might discover there."

DAVID WETTERGREEN

Automated science in Planetary Exploration requires the robot to use the topography of the terrain and the terrain's makeup material types to estimate how difficult it will be for the rover to reach a specific location.



> “The rover did very well on its own. Even under high-risk simulations, there were still plenty of areas for the rover to explore, and we found that we still made interesting discoveries.”
>
> ALBERTO CANDELA (SCS 2021)



correctly without needing additional measurements, it may choose to explore somewhere new. If the robot’s confidence is low, however, it may decide to continue to study the current area and improve its mineralogical model.

The researchers determined risk through a model that uses the topography of the terrain and the terrain’s makeup material types to estimate how difficult it will be for the rover to reach a specific location. A steep hill with loose sand could doom a rover’s mission — a real concern on Mars. In 2004, NASA landed twin rovers, **Spirit** and **Opportunity**, on Mars. Spirit's mission ended in 2009 when it became stuck in a sand dune and its wheels slipped when it tried to move. Opportunity carried on and worked until 2018.

Zoë, a rover that for decades has tested technologies for autonomy, used a previous version of this model during experiments in 2019 in the Nevada desert.

Wettergreen and Candela tested their framework using real Mars surface data. The pair sent a simulated rover scurrying about Mars using this data, charting different paths based on varying risk, and then evaluated the science gained from these missions.

“The rover did very well on its own,” Candela said, describing the simulated Mars missions. “Even under high-risk simulations, there were still plenty of areas for the rover to explore, and we found that we still made interesting discoveries.”

This research builds on decades of RI work investigating autonomous planetary exploration. Papers stretching back to the 1980s proposed and demonstrated methods for allowing rovers to move autonomously across the surface of other planets, and technology developed through this research has been used on recent Mars rovers.

Pioneering autonomous technology researchers at CMU proposed **Ambler**, a self-reliant, six-legged robot that could prioritize its goals and chart its own path on places like Mars. The team tested the six-meter-tall robot in the early 1990s. More rovers followed, including **Ratler, Nomad** and **Hyperion** — a rover designed to follow the sun as it travels to charge its batteries.

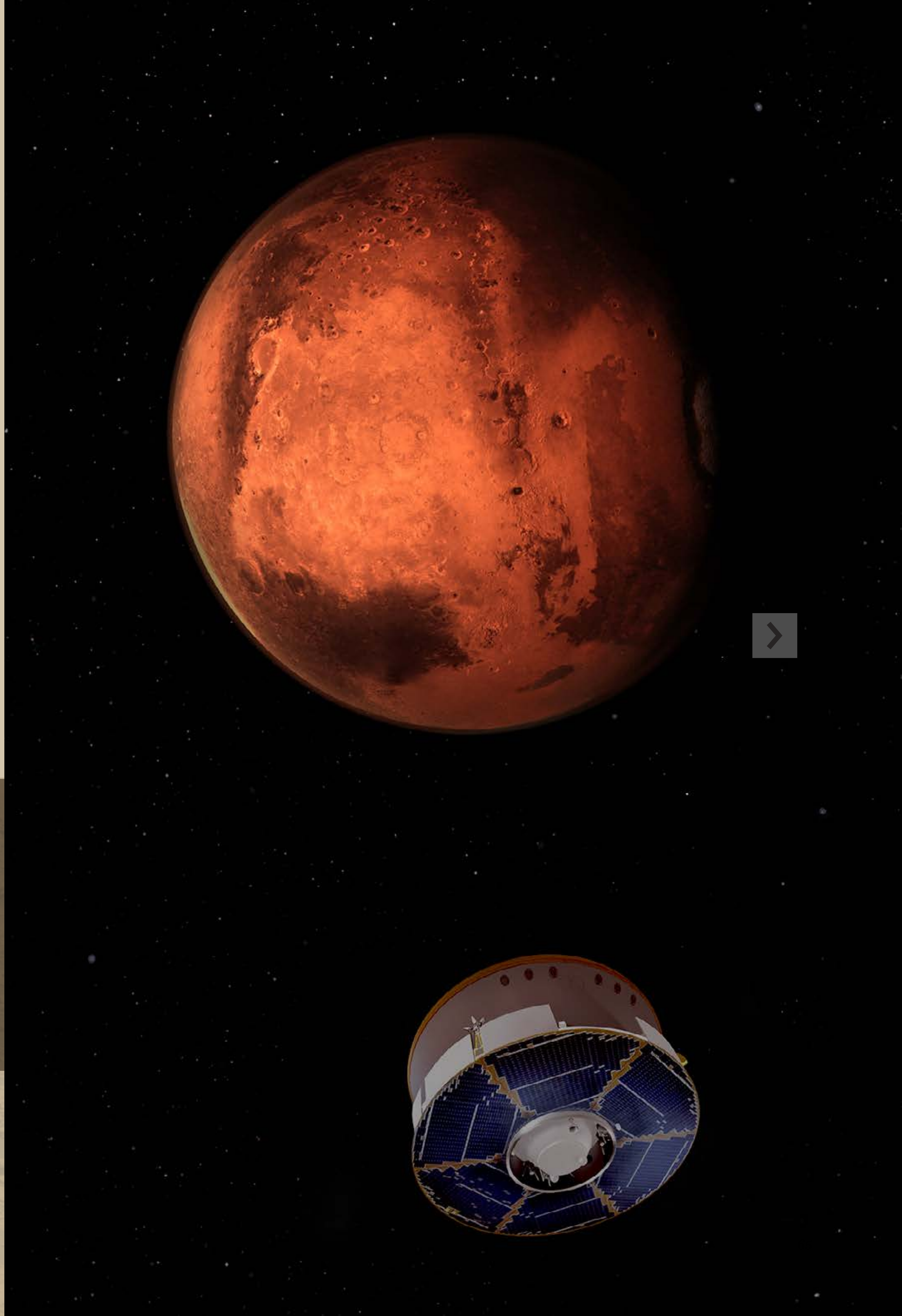
Zoë began its work in harsh environments in 2004 and has traveled hundreds of miles in Chile's Atacama Desert, an environment in many ways similar to Mars. By 2012, Zoë's missions in the desert shifted to focus on autonomous exploration and the decisions behind where to go and what samples to collect. A year later, the rover autonomously decided to drill into the desert soil, and it discovered what turned out to be unusual, highly specialized microbes, demonstrating that automated science can result in valuable discoveries.

Candela and Wettergreen hope to test their recent work on Zoë in the Utah desert. The pair also see their research making valuable contributions to future lunar exploration. Their approach could be used by scientists as a tool to investigate potential routes in advance and balance the risk of those routes with the science that could be gained. The approach could also assist a generation of autonomous rovers sent to the surface of planets to conduct science experiments without the need for continuous human involvement. The rover could assess the risk and reward before charting its own course.

"Our goal is not to eliminate scientists, not to eliminate the person from the inquiry," Wettergreen said. "Really, the point is to enable a robotic system to be more productive for scientists. Our goal is to collect more and better data for scientists to use in their investigations." ■

"Our goal is not to eliminate scientists, not to eliminate the person from the inquiry. Really, the point is to enable a robotic system to be more productive for scientists. Our goal is to collect more and better data for scientists to use in their investigations."

DAVID WETTERGREEN



MARS 2020

and Beyond

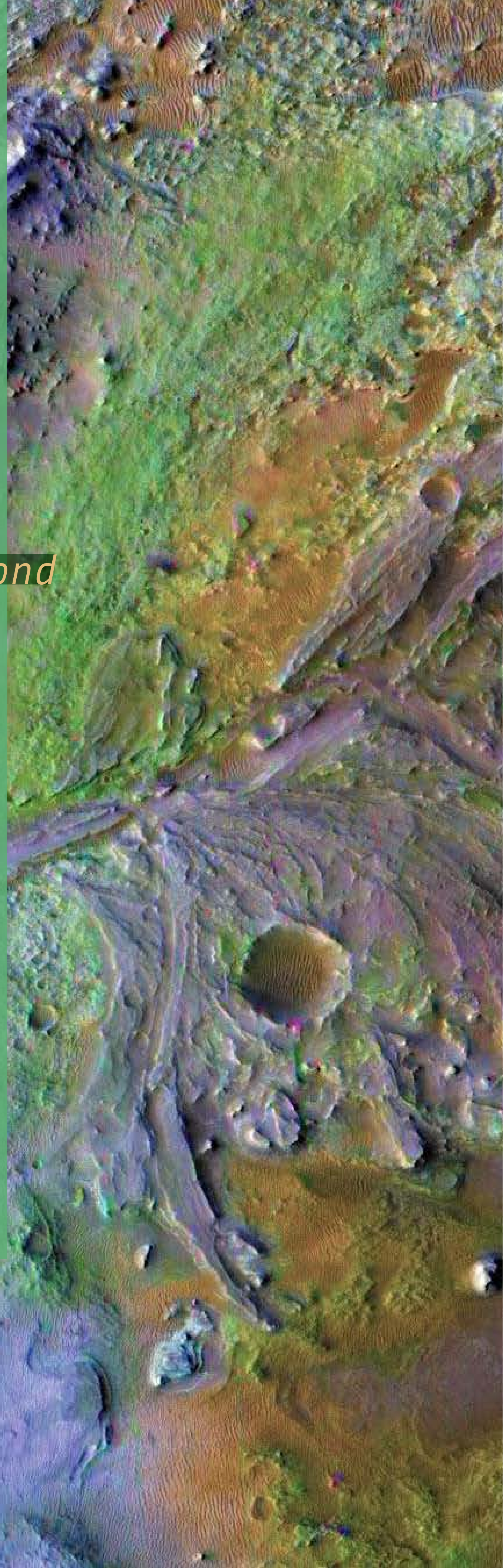
SCS Alumni Discuss Current and Future Space Exploration

KEVIN O'CONNELL

With so much emphasis on SCS' Moon Missions, it's sometimes easy to forget that SCS alumni remain fast at work on the mission to Mars and are involved with plans for missions beyond. A virtual panel discussion held in May 2022 and hosted by Martial Hebert, dean of SCS, revealed some key insights into the future direction of the space programs in the U.S., and some thoughts on potential destinations space program scientists might set their sights on next.

As this panel discussion indicates, SCS alumni remain highly influential and sought after for all aspects of space exploration. What you will read is a summation and excerption. The full webinar, which can be viewed in its entirety online at:

https://www.youtube.com/watch?v=EH6mwGfhvRE



The Mars 2020 Panelists

Andrew Johnson (SCS 1997)

PRINCIPAL ROBOTICS SYSTEM ENGINEER,
NASA JET PROPULSION LABORATORY

Since joining JPL in 1997, Andrew E. Johnson has been developing technologies and flight systems for autonomous navigation and mapping during descent to planets, moons, comets and asteroids. For the Mars Exploration Rovers, he was lead developer for the Descent Image Motion Estimation System, and on Mars 2020 he led the development of the Lander Vision System that provided surface relative position estimates for Terrain Relative Navigation. He was also the manager of the Mars 2020 Guidance Navigation and Control subsystem which included cruise, EDL and surface mission functions.

Emily Newman (SCS 2019)

SOFTWARE SYSTEMS ENGINEER, NASA JET PROPULSION LABORATORY

Emily Newman joined JPL in 2019 shortly after graduating from Carnegie Mellon University with an undergraduate degree in computer science and robotics. She was the lead developer for the telemetry processing backend of the Mars 2020 Entry Descent Landing visualization, which was used to display Perseverance's landing live to millions of viewers. She has also worked on other projects within the Mission Control Systems section, including a cybersecurity network visualization and a system for storing mission data. She currently works on robotic operations for the Curiosity rover.

Vandi Verma (SCS 2002, 2005)

DEPUTY MANAGER FOR MOBILITY AND ROBOTICS SYSTEMS,
NASA JET PROPULSION LABORATORY

CHIEF ENGINEER OF ROBOTIC OPERATIONS FOR
MARS 2020 PERSEVERANCE & INGENUITY

Vandi Verma has worked on space robotics, AI research and technology development and has designed, developed and operated rovers on Mars. She leads about 170 JPL roboticists developing new technology for future missions and working on a variety of JPL robotic missions. She has been engaged in robotic operations on Mars since 2008 with the Mars Exploration Rovers Spirit and Opportunity, Curiosity rover, Perseverance rover and Ingenuity helicopter.

The Landing

When Andrew Johnson (SCS 1997), principal robotics system engineer for NASA's Jet Propulsion Laboratory, first started at JPL, the Pathfinder rover had recently landed on Mars. It did so without much use of computer vision. Since this field of study had always been his focus, Johnson strived to apply computer vision to the landing apparatuses for future planetary exploration missions.

"That's been my objective my entire career – to increase the vision and the autonomy of the spacecraft when they're landing," said Johnson.

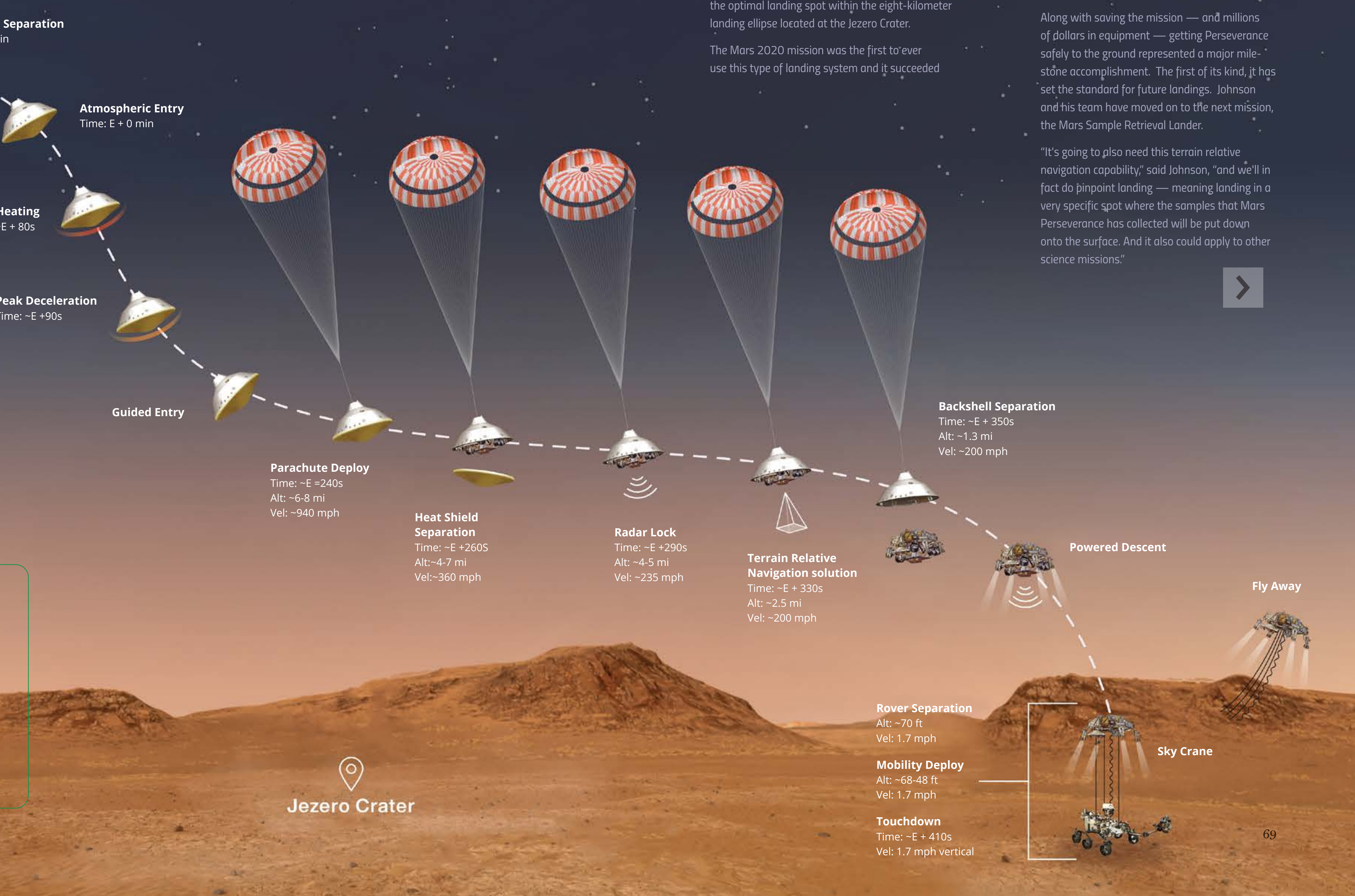
It was a perfect match of Johnson's passions and JPL being the precise place for them. Johnson helped design the Lander Visual System (LVS) for the Mars Perseverance rover. The LVS is a terrain-relative navigation system which operates during the parachute phase of the landing. The LVS takes a sequence of images and matches landmarks in them to a map built from satellite imagery. This helps the lander to see where it is, relative to the surface, and allows the onboard system to target the optimal landing spot within the eight-kilometer landing ellipse located at the Jezero Crater.

The Mars 2020 mission was the first to ever use this type of landing system and it succeeded despite hazardous conditions. Jezero Crater, comprised of steep cliffs from an ancient river delta, large craters, inescapable dune fields and boulder fields, presented many challenges to finding a safe landing spot.

"The system had enough fuel on board to divert to a safe location," said Johnson. "It did not have enough fuel, however, to go to a very specific point. So, the system targeted one of the safest locations that was nearby."

Along with saving the mission — and millions of dollars in equipment — getting Perseverance safely to the ground represented a major milestone accomplishment. The first of its kind, it has set the standard for future landings. Johnson and his team have moved on to the next mission, the Mars Sample Retrieval Lander.

"It's going to also need this terrain relative navigation capability," said Johnson, "and we'll in fact do pinpoint landing — meaning landing in a very specific spot where the samples that Mars Perseverance has collected will be put down onto the surface. And it also could apply to other science missions."



Andrew Johnson (SCS 1997), principal robotics system engineer for NASA's Jet Propulsion Laboratory

The Roving

Before the Sample Retrieval Lander travels to Mars, **Vandi Varma** (SCS 2005), chief engineer of robotic operations for Mars 2020, has work to do on the surface operations side of the mission, driving the **Perseverance** rover — her fourth Mars rover — and the Ingenuity helicopter around the planet's surface collecting samples with the goal of studying the geology and astrobiology of Mars, and preparing for the arrival of astronauts. The Jezero Crater River Delta was chosen because it has the highest likelihood of finding signs of life on the red planet.

"We've got an instrument that can synthesize oxygen from the atmosphere," said Varma. Access to plenty of oxygen is critical to the success of any mission to Mars with humans. "The main part of this mission is to core," said Varma, which means to "have a robotic drill that cores under the surface, collect sample cores, intact and caches them for subsequent return to Earth." Varma points out that it will be the first time samples from Mars will be brought back to Earth.

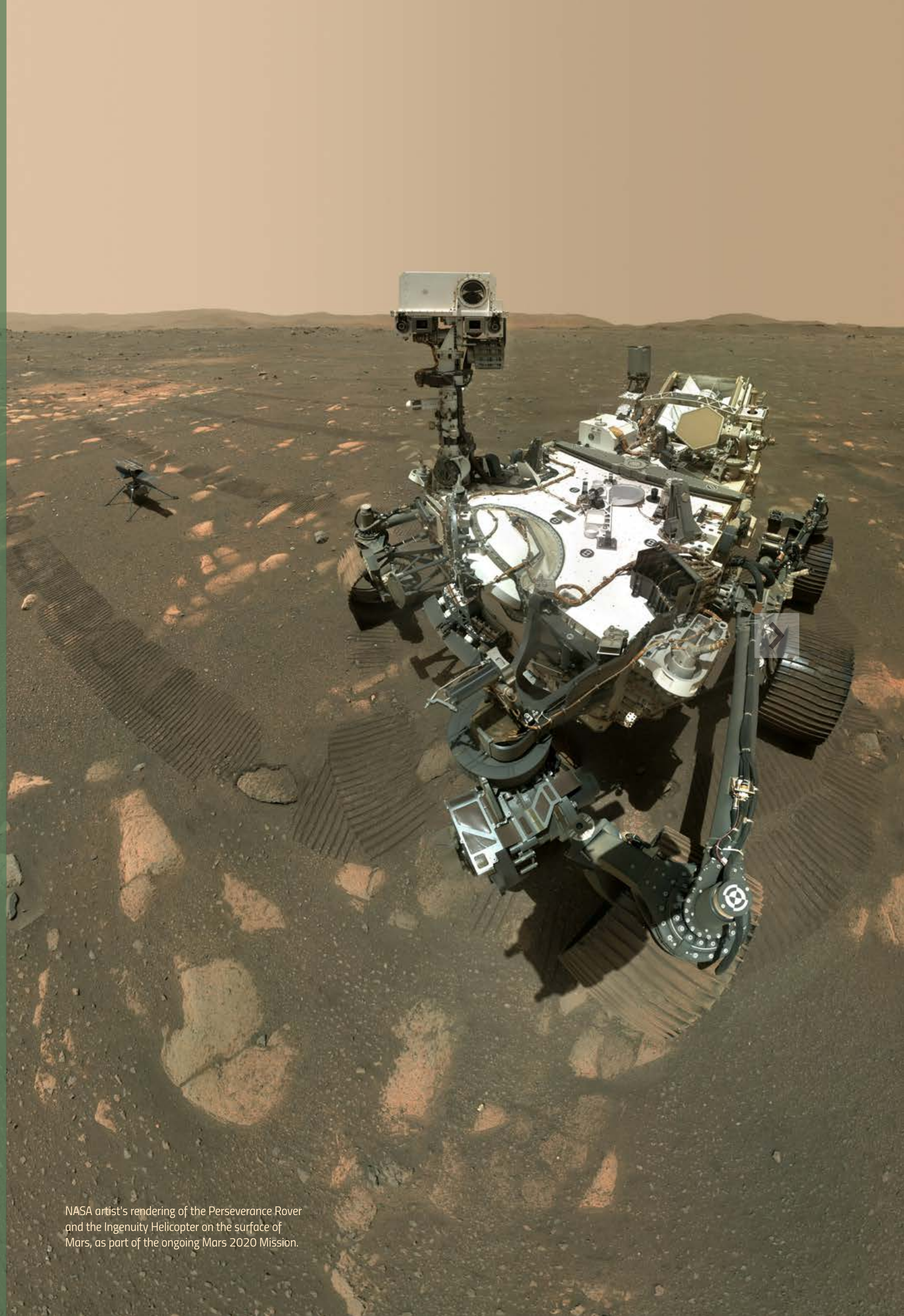
Vandi Varma (SCS 2005), chief engineer of robotic operations for Mars 2020

Communicating with a planet as far away as Mars remains a slow business. It takes 24 minutes for the team to send a message to the rover telling it where to go next. Three towers located around the globe make up the antenna that keeps the team in contact with Perseverance, but it takes time to analyze what the rover is seeing and communicate its next move.

As a result, some level of autonomy assisted Perseverance's forward progress. Because the LVS lander chose a slightly different location for the safety of the landing, Perseverance had to cover extra ground to make its way back to the river delta region of the Jezero Crater. To accomplish this, the team utilized information gathered from the Ingenuity copter as well as Perseverance's own autonomous navigation to arrive as quickly as possible. The team tells Perseverance the targeted locations goal and it uses autonomy to avoid hazards. Using computer vision, stereo processing with cameras and a lot of algorithms for how it models uncertainty onboard, the rover then combines this information with its autonomous algorithm to decide the best path.

Another navigation tool at the team's disposal were the images gathered by the Ingenuity helicopter. "We'd send it ahead to scout out areas and see if we really wanted to send the rover there, and that was very valuable," said Varma.

The autonomous navigation resulted in Perseverance covering five kilometers in just three weeks, which is "kind of unheard of in planetary robotics terms," said Varma. And Ingenuity has proven more durable than originally thought. "Ingenuity was supposed to last for three flights," said Varma. At the time of this publication, that number was 33 flights.



NASA artist's rendering of the Perseverance Rover and the Ingenuity Helicopter on the surface of Mars, as part of the ongoing Mars 2020 Mission.

The Visualization

While the lander was in its descent — a time known as the seven minutes of terror — the world watched live. And they were able to do so, in part, because of the expertise of **Emily Newman** (SCS 2019), software systems engineer at JPL. Newman and her team built a web-based, real-time visualization for use by the Mars 2020 engineers during the Entry, Descent and Landing (EDL) trajectory design, testing and observation phases of the mission.

"Essentially this started as an engineering tool for EDL engineers," said Newman. "We wrote it for them to use to test their simulations." But the visualization test system became the one used on landing day to show the current status of the spacecraft.

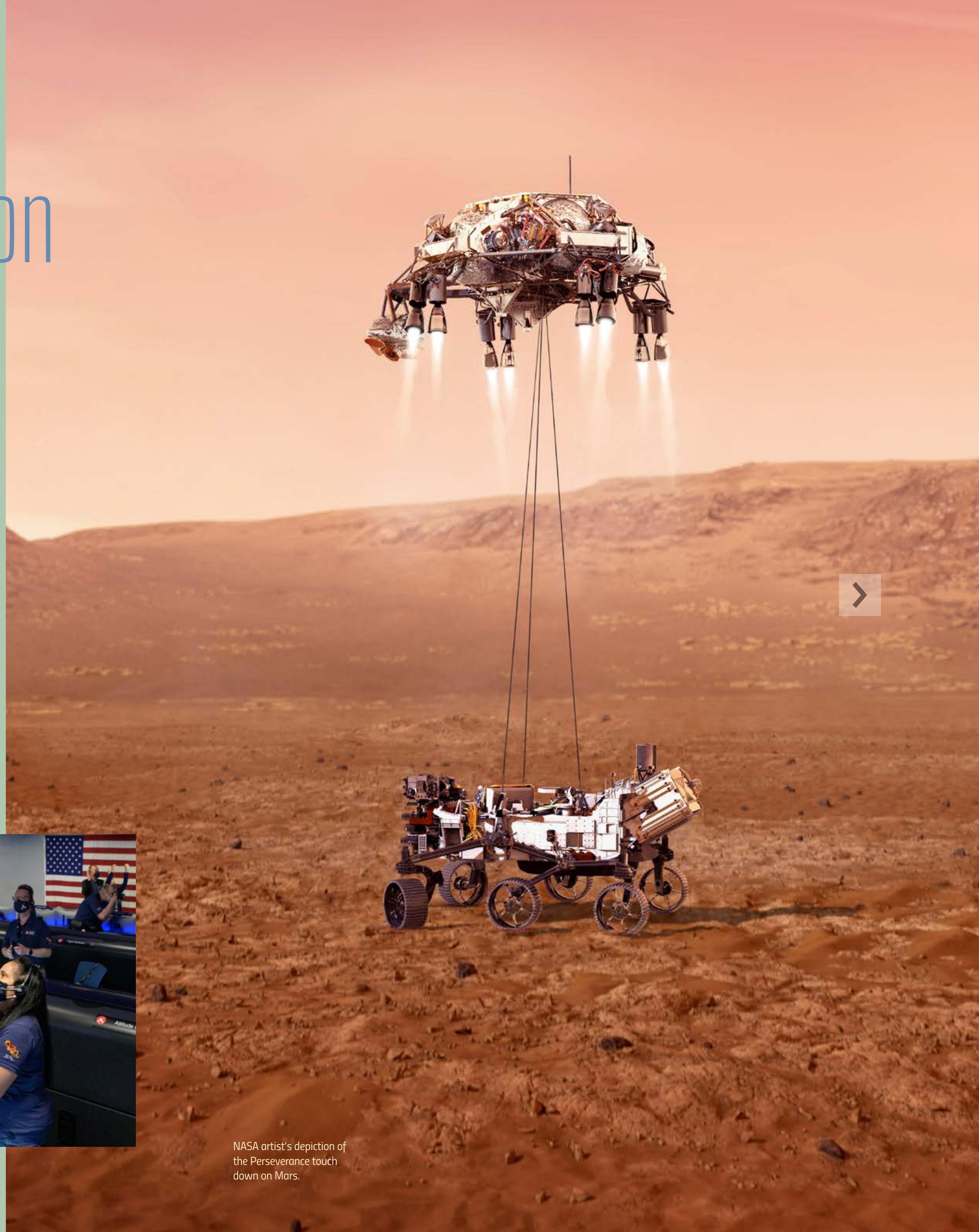
Emily Newman (SCS 2019), software systems engineer at JPL

"We were able to process many different sources of data and then stream it in real time," said Newman. "This included simulation data from MATLAB files, as well as mission support testbed data, which we basically ran in tandem with the testbed for many different sessions and made the webpage available to engineers who were able to watch it while the testbed sessions were running." And, of course, the team also used it during more tests that were specific to the EDL landing scenario.

The stream of the Perseverance landing utilized by the operations teams was also intended to run over NASA TV, which it did. CNN also picked it up and ran it live in Times Square. The stream was viewed by President Biden and essentially anyone in the world who wanted to watch.

"I think it was really cool as a public outreach effort for JPL," said Newman. "An operational system on landing day was just a MacBook Pro laptop, so my manager's laptop was just looking at this web client and streaming it to everybody."

The Mars 2020 team at NASA celebrates the successful landing of the Mars Perseverance rover.



NASA artist's depiction of the Perseverance touch down on Mars.

Where might SCS go Next?

When asked about finding evidence of past life on Mars, Varma spoke optimistically. "We do think we're going to find signs of potential past life, that's kind of why we're there," she said. "And the probability [that life exists] somewhere in the universe, in the solar system, per se. So, we're sending increasingly complex instruments that are able to collect information to piece together the puzzle."

Where to look for that life and where to go next to conduct experiments changes with each scientific discovery. The community of space scientists recently released its Planetary Science Decadal Survey, in which they set the scientific goals of future missions, guiding, in part, what those missions might be. The report identified potential in Enceladus, a moon of Saturn, and the brightest object in the solar system. Covered in ice and with an ocean beneath the ice, Enceladus has plumes coming out of its south pole that could contain material from that ocean.

"That's a very exciting robotic and autonomous mission, to go there and get something from those plumes," said Johnson, "because if there's an ocean, there could potentially be life in the ocean, and if you're sending particles out, you possibly could capture some of that life in those particles. So that's really compelling. That would require new architectures."

The report also lists Europa, a moon of Jupiter that is also icy and contains a global ocean.

"We have Clipper coming up, which will do a flyby of Europa – that's a big mission that JPL is working on with other organizations," said Johnson. "And then there's NASA's push to go back to the Moon."

In order for humans to land on the Moon and for future robotic landings, ongoing development of terrain relative navigation will be coupled with a technology called hazard detection and avoidance, where you build a map of the ground to identify hazards you can't see from orbit.

Newman, Johnson and Varma all pointed to their time at SCS as being highly influential on their careers, and for enhancing their concept of working on teams — especially complex and diverse teams like they encounter at JPL.

"You get to work with experts in a variety of fields who all work together," said Varma. "On that landing day, you feel the sense of teamwork. So, if you like working with a set of people toward a common purpose, the purpose is important … but it's also a lot of fun to work with people who are all very good at what they do."

Enceladus, a moon of Saturn and the brightest object in the solar system, has been listed by the space science community as a potential location for future missions.

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