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V.16.03

A Message from the

Associate Administrator of the

Space Technology Mission Directorate

Dear Colleagues,

For much of its history, NASA has been engaged in the study and development of robots to enhance the Nation's exploration endeavors.

NASA robotic systems serve a variety of functions and seek to enable many different kinds of missions in space. Robotic arms on spacecraft are used to move very large objects in space. The European Space Agency's Rosetta probe recently landed on a comet, illustrating how robotic spacecraft can extend our reach and enable us to visit other worlds, planets, or celestial bodies. Rovers explore the surface of Mars and send data back to Earth, facilitating study of the Red Planet's habitability. Remotely piloted robotic airplanes, like the Ikhana unmanned aircraft system, which captured live video feed of the descent of the Orion Exploration Flight Test 1 in early December 2014, can fly without a pilot on board.

On Earth and in space, NASA is developing, testing, and flying transformative capabilities and cutting-edge technologies for a new future of collaborative human and robotic exploration. In this issue, we've highlighted technologies on board the International Space Station, which provides the astronauts with an ideal test bed for experimentation. We've also featured our continued development of the robotic Exoskeleton, a machine with applications for astronauts working on the surface of distant destinations as well as potential for helping with the physical rehabilitation of people here on our home planet.

In addition to the successful developments in exploration robots, NASA also continues to build public engagement in robotics that will benefit the American economy. The NASA–Worcester Polytechnic Institute Sample Return Robot Competition, for example, seeks to solve technical challenges by mobilizing American ingenuity. This edition also contains examples of private companies and small businesses investing in NASA spinoff technologies to develop robots and software that enhance safety, efficiency, and productivity in industries from healthcare to mining, from disaster relief to manufacturing.

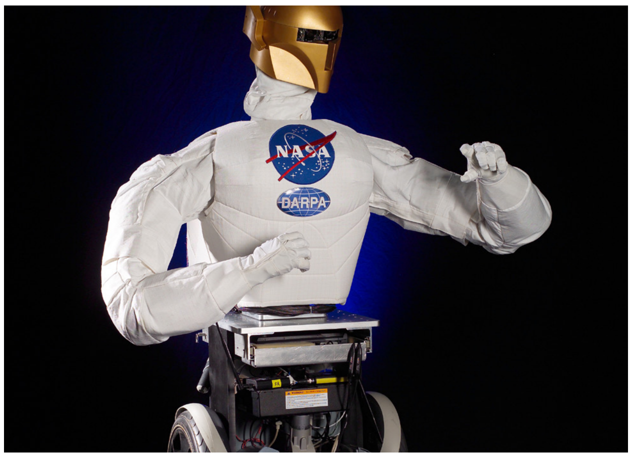
By leveraging partnerships with other parts of NASA, as well as with other government agencies, industry, and academia, NASA is playing a key role in advancing our use of robotic technologies—technologies that drive exploration.

Cheers,

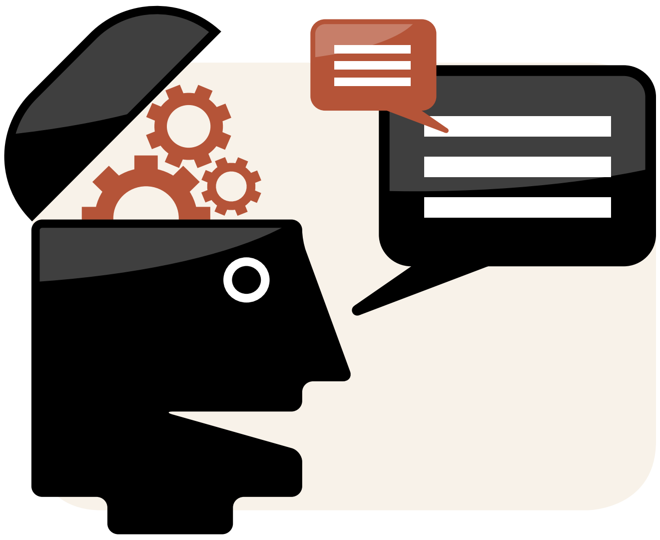
Dr. Michael J. Gazarik
Associate Administrator
Space Technology Mission Directorate
http://www.nasa.gov/spacetech

V.16.03 CONTENTS

FEATURES



SPINOFF HIGHLIGHTS



INSIGHT

ROBOTS

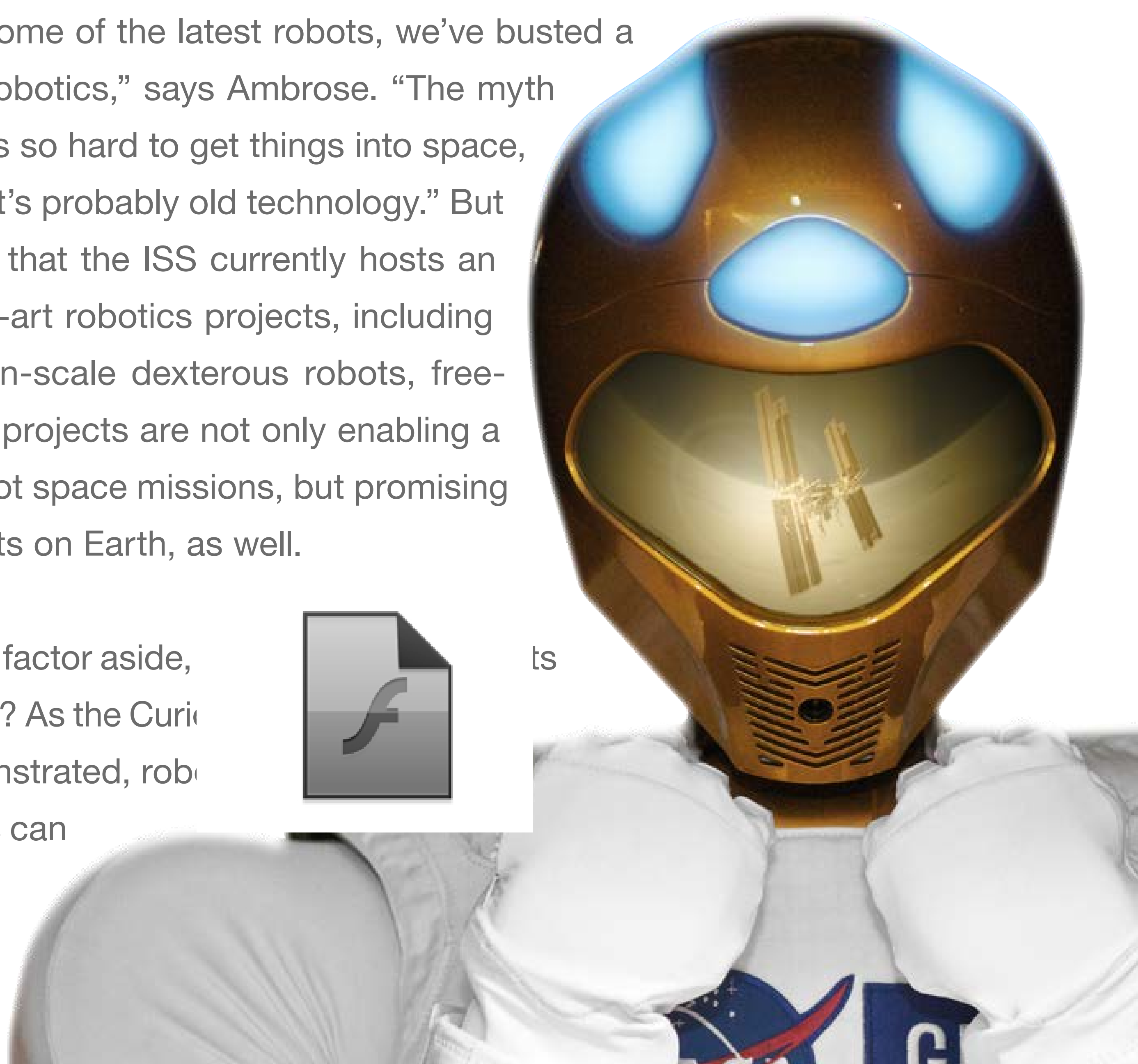
ONBOARD

The International Space Station provides a unique platform for advanced robotics projects that will open the door to a future of enhanced human-robot collaboration in exploration.

“The best robotics laboratory in the solar system.” This is how ***Rob Ambrose***, principal investigator for NASA’s ***Game Changing Development Program*** and chief of the ***Software, Robotics, and Simulation Division*** at Johnson Space Center, refers—without hesitation—to the International Space Station (ISS). Orbiting more than 200 miles above Earth, the ISS is well known as a scientist’s dream, providing a long-term microgravity environment for ***experiments*** in areas from health and medicine to biology, botany, fluid mechanics, and nanotechnology. The ISS has also quickly become an ideal test bed for developing some of the world’s most advanced robotics technology—technology that is on the cutting edge in space exploration and on-the-ground research.

“With the arrival of some of the latest robots, we’ve busted a myth about space robotics,” says Ambrose. “The myth was that because it’s so hard to get things into space, by the time you do, it’s probably old technology.” But Ambrose points out that the ISS currently hosts an array of state-of-the-art robotics projects, including manipulators, human-scale dexterous robots, free-flying robots. These projects are not only enabling a future of human-robot space missions, but promising extraordinary benefits on Earth, as well.

Putting the coolness factor aside, ts
for space exploration? As the Curi
most recently demonstrated, rob
exploration missions can



provide invaluable scientific data and generate a lot of excitement among the public at large. Nevertheless, the big goal has always been for humans to travel deeper into space, for actual people to set foot on Mars, for example. Ambrose explains that robot technology will play a major part in making that happen.

“We have a vision for how robots can fit into human exploration,” he says. The first role is that of a scout: robots would be sent in advance of a human mission to ensure the destination is desirable. A second role would be as a crewmember: robots would support the human crew while in space. A final role would be in a maintenance capacity: robots would be left behind to monitor and repair a facility or continue experiments after the human crew has left.

“Imagine if we can park a facility on the surface of Mars with a robot caretaker and then, years later, launch a human crew to go meet it,” Ambrose says. “That will make our exploration of the solar system more efficient and more flexible. The facility can be up and running for months or years so we know it can be trusted, that it is safe. When the human astronauts arrive, they would be able to focus on jobs like exploring the Martian surface to make amazing discoveries.”

The reality of space travel involves dirty, dull, and sometimes dangerous work to which a robot would be well suited.

[Jobs like exploring the Martian surface]

“Over the years, I’ve asked people, if you had a robot, what would you want it to do for you?” Ambrose says. “Kids always say ‘Do my homework.’ Adults always say ‘Clean the bathroom. Clean the kitchen.’ And when we ask astronauts, they want the robot to do chores too.” Whether the task calls for measuring the airflow from a filter or navigating the risks of an emergency spacewalk, there are multiple tasks involved in space travel that suit robots far better than humans. Robots do not get tired or distracted by the beauty of Earth turning outside the window. And, as Ambrose notes, they can hold their breath for a very long time.

WALK LIKE A ROBOT

With these benefits and more in mind, NASA has been developing generations of a humanoid robot, dubbed Robonaut, since the late 1990s. Together with partner General Motors, NASA envisioned Robonaut as a robot that would not replace people but work alongside them.

"General Motors shared our vision of a robot that can safely work next to people and that can work with the same interfaces built for people. The whole point of the Robonaut system is that it's going to be working near people and working with them safely," Ambrose says.

The second generation Robonaut, ***R2***, made history as the first robot crewmember of the ISS when it arrived at the Space Station in 2011. Possessing remarkable dexterity and designed to ultimately assist ISS crewmembers in maintaining the Station, R2 lacked a key part: legs. That changed this year when NASA partner SpaceX delivered R2's unique lower half to the ISS on Sunday, April 20.

R2's new legs are its least humanoid feature. With seven joints each and, instead of feet, grasping "end effectors" equipped with camera eyes, R2's legs are more reminiscent of tentacles than of human parts. Nevertheless, this new addition to the R2 allows it to move about inside the ISS and extend its assistive capabilities beyond measuring the flow of air filters. Studies are under way to demonstrate R2's potential to perform telemedicine—conduct ultrasound examinations and administer medications while being remotely controlled by doctors on the ground. "We're very excited that these legs will give R2 the mobility it needs to climb around inside the Space Station," says Ambrose, though he acknowledges that R2 will hardly be swinging from module to module like a monkey. "It will always be required to have one foot down at a time, and it will move rather slowly throughout the Station. But with a robot, what's the rush?" Ambrose adds.

Even as R2 is in the process of gaining its mobility, NASA and its partners are applying technology derived from the Robonaut program—most recently, the R5 robot—to help people on Earth regain theirs. NASA teamed with the Institute for Human and Machine Cognition in Pensacola, FL, which had already been developing exoskeleton technology to help people who had lost the ability to walk and required assistance moving. The collaboration, in a mere 9 months and with a team of five to six people, resulted in the ***X1 exoskeleton*** based on Robonaut technology. The team soon realized that not only could the X1 potentially allow people with physical injuries or neurological conditions to walk again, it could also be used to measure astronaut strength in space in order to assess the effectiveness of exercise routines designed to combat the debilitating effects of long-term living in microgravity.

[measuring astronaut strength in space]

"It just goes to show that when you do some research, sometimes it leads to an application that you would have never imagined," Ambrose says.

REMOTE POSSIBILITIES

R2 is not autonomous; it is controlled either by ISS crewmembers or by researchers on the ground. Another pair of remotely controlled robot projects based on the ISS are also adding to the possibilities of human-robot space exploration.

“At the most basic level, what we are trying to do is improve the way that humans can live and work in space by using remotely operated robots,” says ***Terry Fong***, director of the Intelligent Robotics Group at Ames Research Center. As with R2, Fong and his colleagues look at ways robots can take over repetitive, routine maintenance tasks to allow astronauts the time to pursue more complex endeavors. “Things that actually require more brain power than changing a filter,” Fong explains. Another goal is to extend astronauts’ reach far beyond the bulkhead of the spacecraft. According to Fong, this advancement would allow astronauts in a spacecraft orbiting Mars to use robots to accomplish tasks on the surface.

This latter purpose is central to the ***K10 project***. K10, Fong explains, is a four-wheeled mobile research rover designed to be “much more interactive than the current rovers we use on Mars.” The robot is equipped with sensors and software that allow it a measure of joystick independence. “K10 is meant to be fairly intelligent from the standpoint of being able to get from point A to point B by itself,” Fong says. The K10 project has focused on determining the best software configuration to allow an astronaut in a spacecraft to remotely operate the rover.

This summer, three ISS crewmembers separately tested K10 from orbit, remotely controlling the robot on Earth to do a survey of an area like a civil engineer would do at a construction site, to deploy a simulated telescope, and to take pictures and measurements of the deployed telescope. "In all three cases," says Fong, "we have astronauts in space working on the ground essentially by using an avatar, a mobile robot that's doing the work in place of the astronaut."

The second telerobotics project, Fong explains, originated as an undergraduate research project at the Massachusetts Institute of Technology. Created as a platform for studying satellite control, the three volleyball-sized ***Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES)*** have been residents on the ISS since 2006 and have been used for experimentation more than any other device or system on the Station. When Fong's Ames team took over management of the SPHERES about 3 years ago, they began exploring ways to transform the SPHERES from satellite control test beds to free-flying robots complete with sensors, cameras, and remote control features.

[Control testbeds into free flying robots]

"We were sitting around thinking about how to turn these SPHERES into robots, and everyone was playing with their smart phones. That's when it dawned on us: What if you took smart phones and put them on the SPHERES?" says Fong. This presented no easy task; the team had to make the smart phones safe for use on the ISS. This meant protecting the glass screens from shattering—shards of glass are a significant hazard in microgravity. (Teflon tape solved this problem.) Then the team had to remove parts of the smart phones' hardware to prevent them from generating radio frequency interference. "Airplane mode is not good enough for space," Fong explained. "We need to have Space Station mode." In 2011, astronauts installed the modified smart phones on the SPHERES, creating Smart SPHERES.

"With only a couple of modifications, you use something that cost[s] a few hundred dollars that would have cost many thousands more to engineer yourself," Fong says. Now controlled from the ground, the Smart SPHERES are opening the door to a range of new robot assistance capabilities. "To date, there has never been a free-flying mobile camera that mission control can actually fly around inside the Space Station," Fong states. "We can use the SPHERES for doing video surveys inside the Station. And we're adding different instruments to them to measure the quality of the air, to do inventory, and to measure light and sound levels—things that require routine, repetitive measurements. All from this free-flying robot."

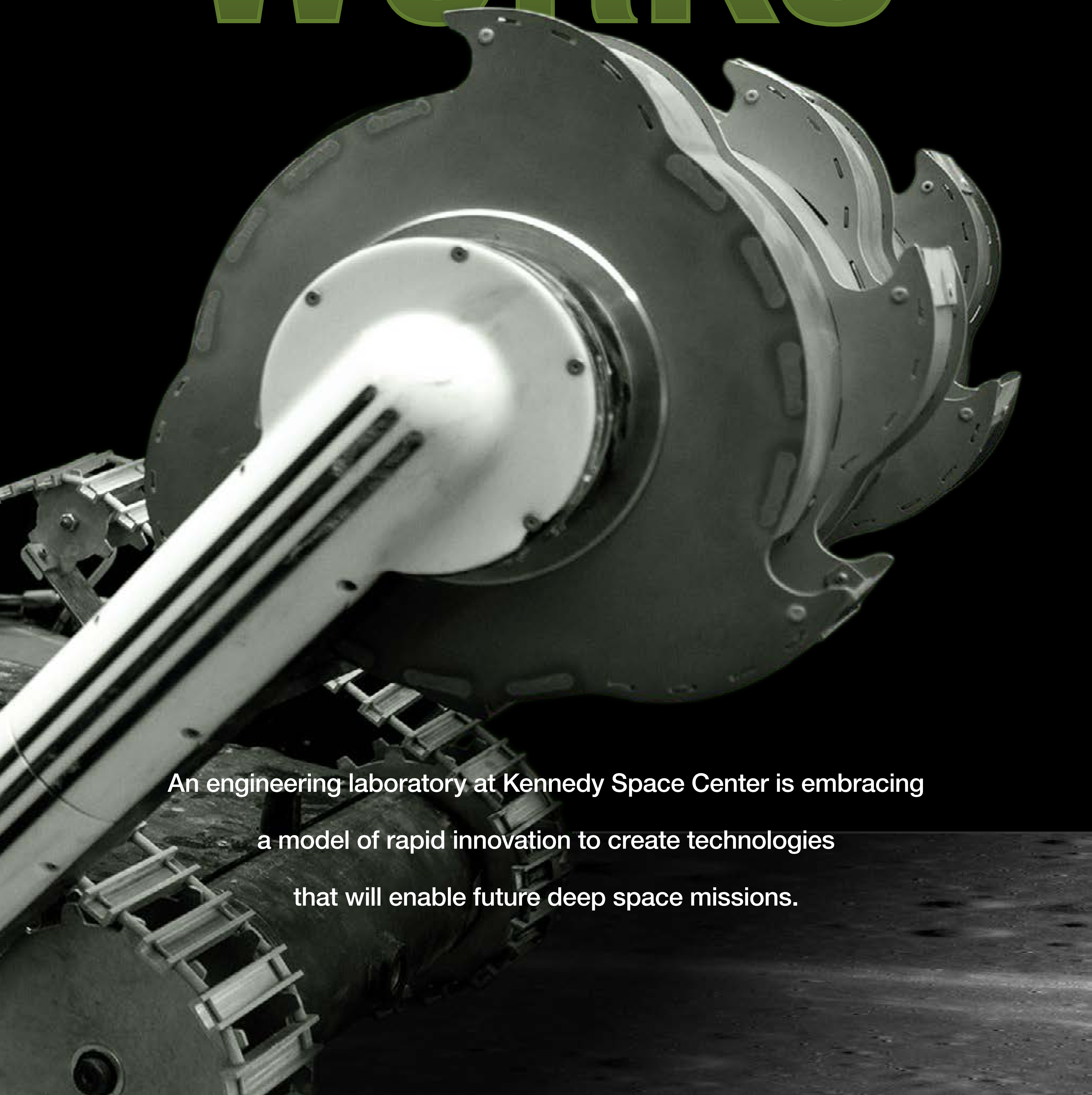
Soon, the Smart SPHERES will get "brain upgrades." Later this year, ***Project Tango*** prototype smart phones, developed by Google, will arrive on the ISS. Once installed on the SPHERES, the robots will be able to navigate even more effectively, thanks to the phone's ability to track its position and orientation and to create a 3D map of its surroundings.

Thanks to the unique research opportunities provided by the ISS, projects like SPHERES, K10, and Robonaut are rapidly expanding the role of robotics in space exploration, ensuring that future missions will be able to combine the advantages of both human and robot capabilities.

“This is probably one of the most exciting times to be working at NASA,” Fong says. “Regardless of where NASA goes, robots are going to be there. If humans go back to the Moon, or to an asteroid, or Mars, robots are going with them.”

“There is no longer a divide between human exploration and robotic exploration,” Fong adds. “That’s why when I wake up in the morning, I just can’t wait to get to work.”

IN THE WORKS



An engineering laboratory at Kennedy Space Center is embracing a model of rapid innovation to create technologies that will enable future deep space missions.

The technology development process often goes hand in hand with the need to problem-solve. A robot scooped up loads of icy regolith simulant—comparable to the soil of the Moon or Mars. But the ice melted, and getting the wet regolith out of the buckets proved difficult. Another robot took off on a tethered test flight only to damage itself as it ricocheted off a wall.

Failures? Perhaps. But not the sort that concern ***Jack Fox***.

"If you don't fail every now and then, you're not pushing the limits of technology," says Fox, chief of Kennedy Space Center's Surface Systems Office. Now Fox and his Kennedy colleagues are running a hotbed of innovation that harkens back to NASA's Apollo era even as it develops the technology necessary for the future of space exploration. Fox and his colleagues take pride in their program motto: *Fail Fast Forward*.

About 3 months before the end of NASA's Space Shuttle Program in 2011, Fox recalls, "We said, 'This is the end of an era for NASA. What will the next era be like?'" Fox and his colleagues discussed the likelihood of a better balance between commercial and Government endeavors, with more partnerships and university involvement. There would probably even be a greater focus on smaller, robotic devices. A key question then arose among Fox and his colleagues: “How do we organize ourselves in this new era?” As the team considered the issue, Fox recalls, “Somebody said, ‘We need to be a Skunk Works.’”

Launched in the early 1940s, Lockheed Martin’s famous Skunk Works was the birthplace of iconic aircraft such as the SR-71 Blackbird and the F-117 Nighthawk. Skunk Works operated using a “lean, hands-on development” philosophy, Fox explains, that valued rapid prototyping as a method to quickly advance and optimize new technologies and designs. This approach shared characteristics with the Apollo Program and Wernher Von Braun’s rocketry work for NASA. The team tailored the Skunk Works model to a 21st century NASA, with a strong emphasis on safety, and in 2012, in a Kennedy facility that once hosted moonwalk rehearsals for Apollo astronauts, Fox and his colleagues founded Swamp Works.

Swamp Works focuses on solvi  rea of surface systems—basically, spaceports in space, dy Space Center has a legacy of developing spaceports We extended that vision.” Surface systems focus not on the an habitats in space, but

on technologies that support the arrival and departure of vehicles from locations like the Moon or Mars. "You need a landing pad, a launch pad, capabilities to generate propellants from local resources to power vehicles to leave and come back," Fox says. Surface systems technologies also focus on recapturing and reprocessing wastes from human habitats that could be turned into feedstock for 3D printing or fertilizer to grow food.

Swamp Works envisions semiautonomous RASSORs swarming over a planetary or asteroid surface

Swamp Works has projects under way that have borne fruit in the mere 2 years the lab has been in existence. One of them is a solution for excavating in a microgravity environment. Excavating and processing the soil, or regolith, of a place like Mars or the Moon will likely be necessary to provide everything from potential fuel to water, oxygen, and building materials. But a major problem with digging in microgravity, Fox says, "is every force has an equal, opposite reaction force. So if you try to dig, the same force you're digging with will push you away from where you're trying to dig." To address this issue, Swamp Works developed the *Regolith Advanced Surface Systems Operations Robot (RASSOR)*. RASSOR is equipped with twin rotating bucket collectors that help anchor the robot to the ground as they dig, and the robot's tank-like treads, along with its collectors, allow it to navigate rugged terrain. Swamp Works envisions semiautonomous RASSORs swarming over a planetary or asteroid surface, gathering the necessary materials to sustain a deep space mission.

de the Oxygen and de (OVEN)—designed d analyze regolith, g key resources like oxygen and water—and the Extreme Access flying robot that, similar to RASSOR, could travel down into the dark bottoms of craters to collect potentially water-rich regolith and return it to processing plants on the crater's rim. Swamp Works also developed a pair of percussive excavators dubbed *VIPER* and BADGER in collaboration with NASA's Jet Propulsion Laboratory.

The design of the RASSOR robot makes use of both its treads and its twin scooping arms to traverse difficult terrain. RASSOR's rotating scoops hold the robot to the ground as it gathers regolith. This design allows the robot to dig effectively, even in microgravity.

These technologies and others derive from an environment designed to encourage collaborative innovation and the working through of ideas. Swamp Works has a coffee shop–style innovation space replete with circular tables and white boards where groups gather to hash out fixes for problems in ongoing projects or envision new solutions to existing problems. Swamp Works also boasts a diversity of backgrounds among its staff—fresh-out-of-college engineers mingling with scientists with years of experience.

"There is age diversity, background diversity," Fox says. "There's the science background and the engineering background. Scientists tend to think creatively. Engineers can make the creative a reality, but may not come up with the most creative solutions alone. You need both kinds of people."

And you need partnerships. "If you get government, industries, and universities lined up, great things can happen," Fox adds. Swamp Works collaborates with commercial space enterprises and other NASA Centers. Its technologies are attracting commercial attention; Swamp Works has engaged in discussions with commercial companies exploring the potential of space mining operations. In addition, its partnerships with Florida universities are bringing students into the Swamp Works labs to lend fresh perspectives and gain valuable experience.

Testing and tweaking. Knocking out early prototypes from plywood and PVC. Pushing through generations of a new technology quickly and safely. Rapid-fire trailblazing. Through these various efforts, the Swamp Works model has quickly gained attention within the Agency.

“We thought we would be below the radar, but we’ve popped out above the radar very quickly,” Fox says. “We’re hopeful for more.”

In the meantime, a new kind of bucket solved RASSOR’s sticky regolith problem. An improved tether system and some software fixes got the Extreme Access robot flying again. Swamp Works embraces failure as an essential part of innovation, but only if it moves the technology forward.

“Fail, but learn from it. Make sure it doesn’t happen again,” Fox says of his team’s general philosophy. “Then get back to work.”

BIG STEPS

Thanks to a nationwide initiative led by NASA and fellow agencies, the future of the robotics industry is now.

How do you teach a robot to recover its balance after it's been pushed? How do you teach it to open a door? To write on a whiteboard without mashing the marker to a pulp? To work safely side by side with a human? To shake a hand?

Simple tasks can present significant challenges for robotics engineers. A human writing with a pencil knows, largely without conscious thought, how much pressure to apply when putting pencil to paper. A robot, on the other hand, requires both careful programming and hardware capable of making the subtle adjustments in force necessary to write without snapping the pencil or to staple a sheaf of paper. Commonplace functions humans take for granted—perception, balance, object recognition, and so on—all present complex obstacles for robotics researchers seeking to advance robot capabilities for applications in space and on Earth.

Jerry Pratt and his colleagues at the Institute for Human and Machine Cognition (IHMC) in Pensacola, FL, have been working on what might seem to be a basic human capability but is also one of the most difficult to replicate: walking.

"We've been coming up with various ways of controlling walking," says Pratt, senior research scientist at IHMC. "It is a really interesting and challenging problem, and there is no best solution yet."

Achieving a best solution to the quandary of bipedal robot mobility—and to many other pressing challenges in the field of robotics—is the focus of a nationwide, collaborative effort in which NASA and other Government agencies are partnering with organizations such as the IHMC to position the United States on the cutting edge of robotics technology and support the industry's development for years to come.

THE ROBOTICS INDUSTRY OF THE FUTURE . . .

In 2011, President Barack Obama announced the establishment of the ***National Robotics Initiative (NRI)***. Part of a larger plan to reinvigorate U.S. manufacturing, the NRI brought together NASA, the National Science Foundation, the National Institutes of Health, the Department of Agriculture, and other agencies to launch a multimillion-dollar solicitation to fund the development of robots designed to work in tandem with humans.

[Robots designed to work in tandem with humans.]

Under the NRI, NASA has naturally targeted robotics projects that address challenges unique to space exploration, says ***Rob Ambrose***, principal investigator for NASA's ***Game Changing Development Program*** and chief of the ***Software, Robotics, and Simulation Division*** at Johnson Space Center. The Game Changing Development Program, part of the Agency's ***Space Technology Mission Directorate***, funds NASA's participation in the NRI.

“We’re laying out the NRI to point researchers toward solving hard problems we have in space,” Ambrose says. “We have a number of projects that are targeted for Space Station applications.” These include new sensors and control software, as well as new approaches for controlling robots, such as using an avatar interface to command the machine. These NRI-funded technologies can be tested on the ground, then tested using robots on the International Space Station (ISS).

“We can test the technologies on our Robonaut on the ground, and if they check out, we can then try them out on the Robonaut on the ISS,” says Ambrose. “It’s a great opportunity for a researcher to get access to that robot and to get access to the Space Station as a science laboratory.”

Ambrose describes one NRI-funded collaboration with Carnegie Mellon University that is innovating laser technique for evaluating changes in the soil ahead of a moving rover, allowing it to detect the presence of soft soil that might trap the rover and derail a robotic mission.

“We already lost the Spirit rover on Mars after it got into soft soil, so this project will be great for future rovers,” Ambrose says.

Another NASA partnership through the NRI has teamed the Agency with IHMC. NASA had already partnered with the institute to develop the ***X1 exoskeleton***, wearable robotic technology derived from NASA’s Robonaut and designed primarily to help paraplegic patients regain mobility. The newest NRI project focuses on the development of the humanoid Robonaut 5. Pratt explains that humanoid robots will be useful for future space exploration.

“The humanoid form is really goo asier to understand how to operate,” he says. “You could ha orbit operating humanoid robots on the surface, as if they were human.” IHMC’s NRI work has focused not on creating autonomous functionality for humanoid robots, but semiautonomy that allows for human intervention when necessary.

“What we do in our operating interfaces is to show the footsteps on the ground that the robot is thinking about taking, and if the human operator does not like those footsteps, he can force a change,” says Pratt. And there is the existing challenge of programming robots to walk, in general.

“Imagine you’re walking on stepping stones and you lose your balance or there is a gust of wind and you have to take a step in a way you didn’t plan to. You might flail your arms or lunge to regain your balance," says Pratt. "We have been developing strategies for robots to do that."

… AND THE FUTURE ENGINEERS WHO WILL SHAPE IT

But enhancing robot capabilities is not NASA's only concern. The Agency's participation in the NRI is not limited to advancing the robotics industry now, but also involves fostering new generations of robotics engineers who will carry that industry forward in the future.

"We see the NRI as a pipeline approach to getting the United States back into the lead in robotics," says Ambrose. "You have to play the long game here and think about multiple generations that will come after us and who will do much better work than us."

Ambrose explains that NASA starts getting students excited about robotics at the K–12 level by sponsoring robotics competitions around the country. "This approach has probably impacted the lives of tens of thousands of students," Ambrose says. "These are the premier nerds, the highest caliber nerds in the country, and we've teamed them with some of the best engineers in the country as mentors, and they are doing things today in high school that graduate students could only dream of 10 to 20 years ago."

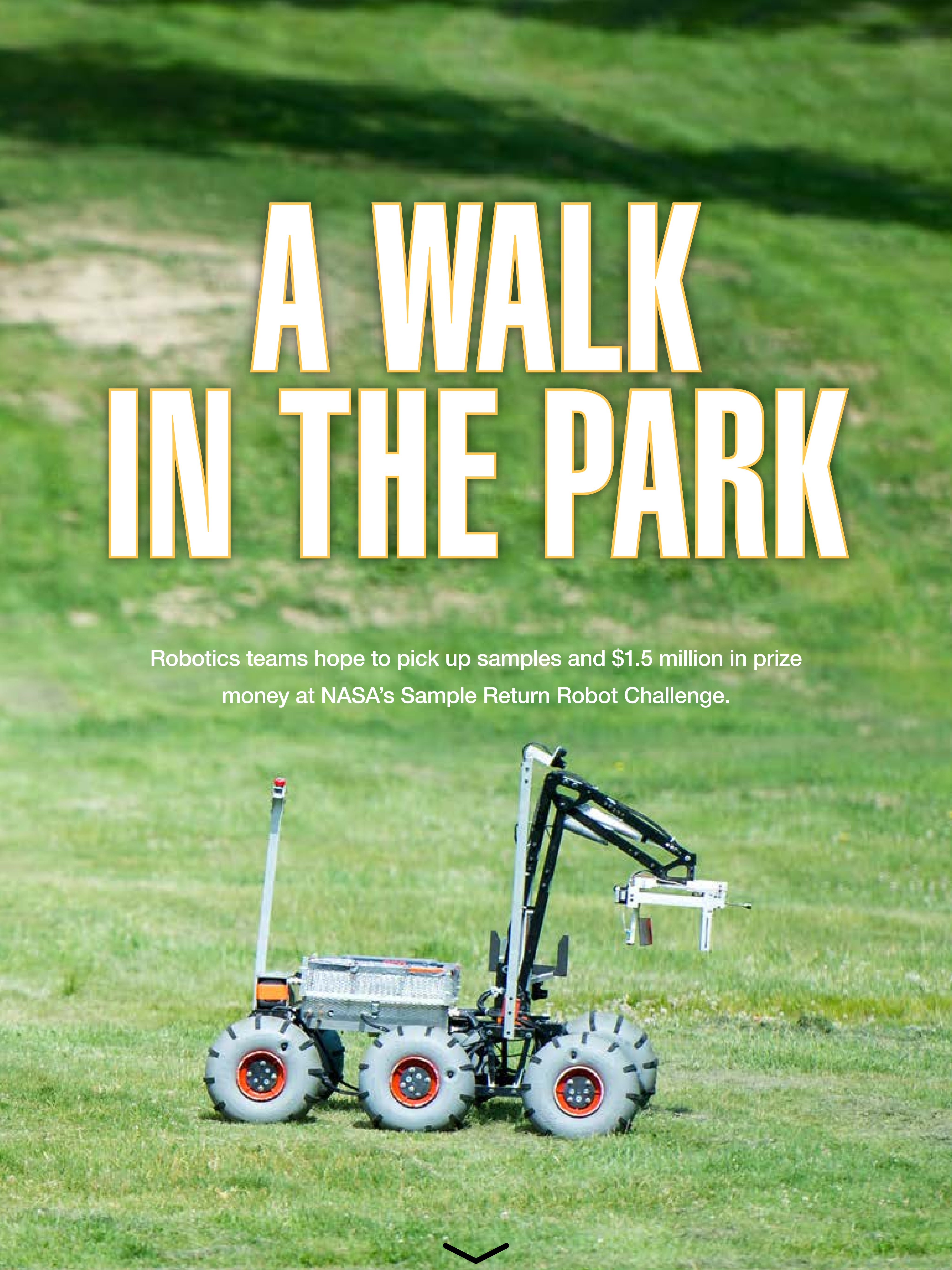
Further down the pipeline, what do these high school students need when they graduate? Ambrose's answer: a university scholarship and professors who care. As part of the NRI, NASA and its fellow agencies have sponsored grants to help high school students pursue an interest in robotics—as well as in other science, technology, engineering, and math disciplines—at the university level.

"We're now seeing students coming out of college who have been building robots since they were 10 years old," says Ambrose. And what do these college students need when they graduate? Easy answer: "They really need a job," says Ambrose. So the final phase of the pipeline, he explains, is to either provide opportunities

for the young engineers at NASA or to find places for them at partner companies. “There are all sorts of jobs that are starting to go robotic,” Ambrose says.

And this is where the future of the robotics industry envisioned by the NRI’s participants starts to take shape, built on the foundation of the game-changing robotics developments NASA and its partners are pursuing now, and advanced by the even more cutting-edge work the next generation of robotics innovators will accomplish.

“It’s a very exciting time in robotics today, and we’re seeing companies start to get it,” Ambrose says. “We would like to feed all of these companies with young people who have the right skills and are highly motivated to go and change the world with the robots they have created.”



A WALK IN THE PARK

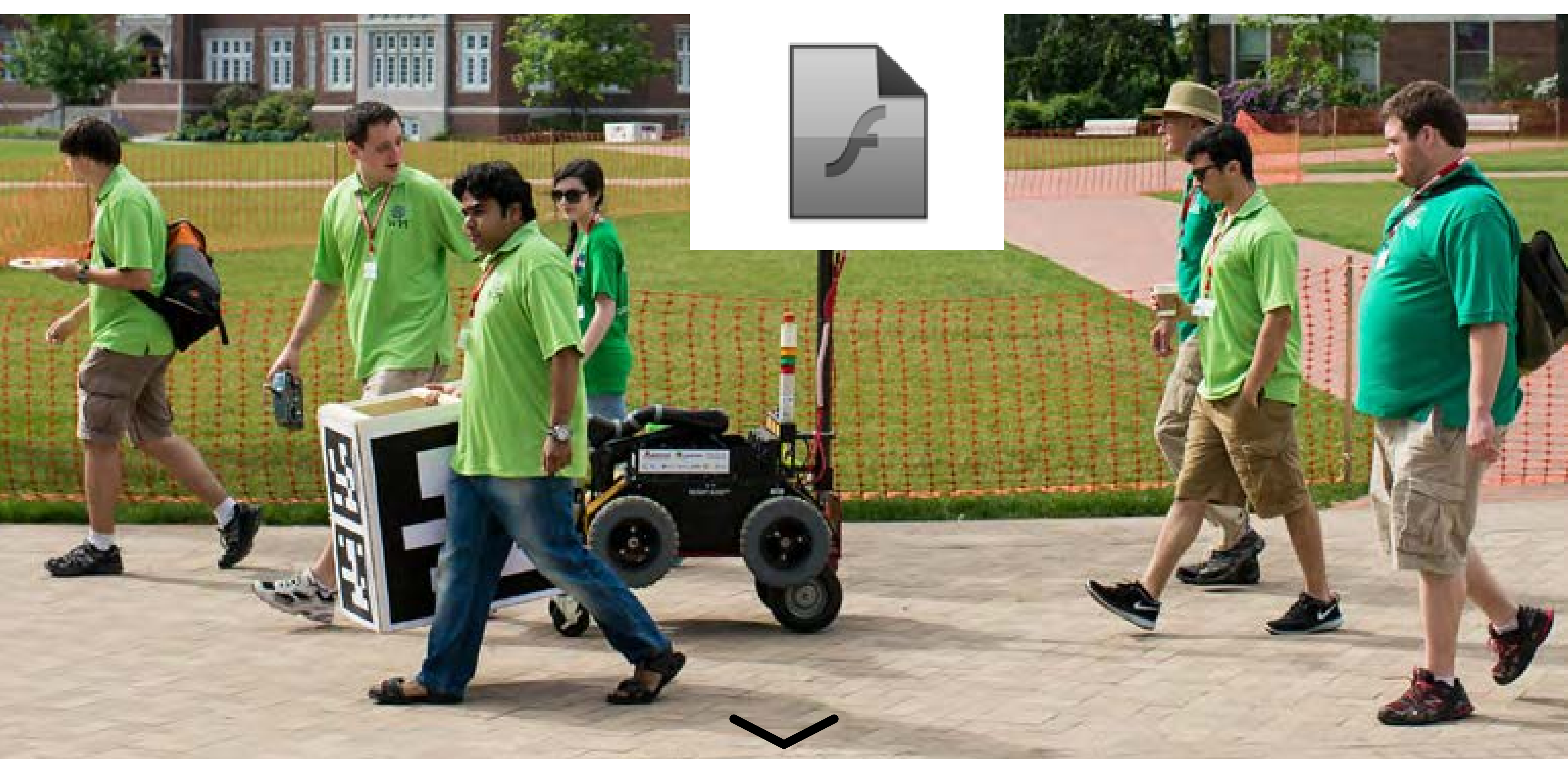
Robotics teams hope to pick up samples and $1.5 million in prize money at NASA's Sample Return Robot Challenge.

Step 1: Build a robot that can roam a park, find and pick up various objects, then return to home base. Step 2: Collect a check for $1.5 million. Simple enough, right?

But, wait! Your robot cannot use any Earth-based capabilities such as GPS or magnetic compassing. Also, it must operate autonomously, without any human control or guidance. And we can't tell you exactly what it's looking for, only that it needs to find it. Or them. You have 2 hours. Good luck.

This is the idea behind NASA's Sample Return Robot Challenge, a part of the Agency's Centennial Challenges prize program. Twenty six teams from across the globe have signed up to test their robots this June in the fourth iteration of the competition, which will once again be held at the Worcester Polytechnic Institute in Worcester, MA.

"The premise may sound simple, but the technology we are looking for is actually quite sophisticated," Centennial Challenges Program Manager Sam Ortega said. "We already have robots that can execute a variety of complex operations, but to be able to do so on their own, without a human prompt, is next-level competency."



Teams must demonstrate a robot that can locate and collect geologic samples from a wide and varied landscape without human control in two levels of competition that increase in difficulty. Level 1 requires finding a known sample in a given location within 30 minutes for a $5,000 prize. Level 2 is considerably harder, with a 2-hour time limit during which the robots must locate as many unknown samples as possible, in completely random locations, for points worth prize money.

The Retrievers team robot is seen attempting the level one challenge at WPI in June 2014. Teams are required to demonstrate autonomous robots that can locate and collect samples from a varied terrain, operating without human control. The competition encourages innovations in robotics technologies. *Photo Credit: (NASA/Joel Kowsky)*

Since the first challenge in 2012, more than 20 teams from the United States and other countries have competed in the event. During the first 3 years of competition, only two teams—Survey of Los Angeles and the West Virginia Mountaineers of Morgantown—completed Level 1 and were eligible to attempt Level 2. This year's 26 registered competitors include a host of universities, small businesses, makers, a retired astronaut, and a group of high school students.

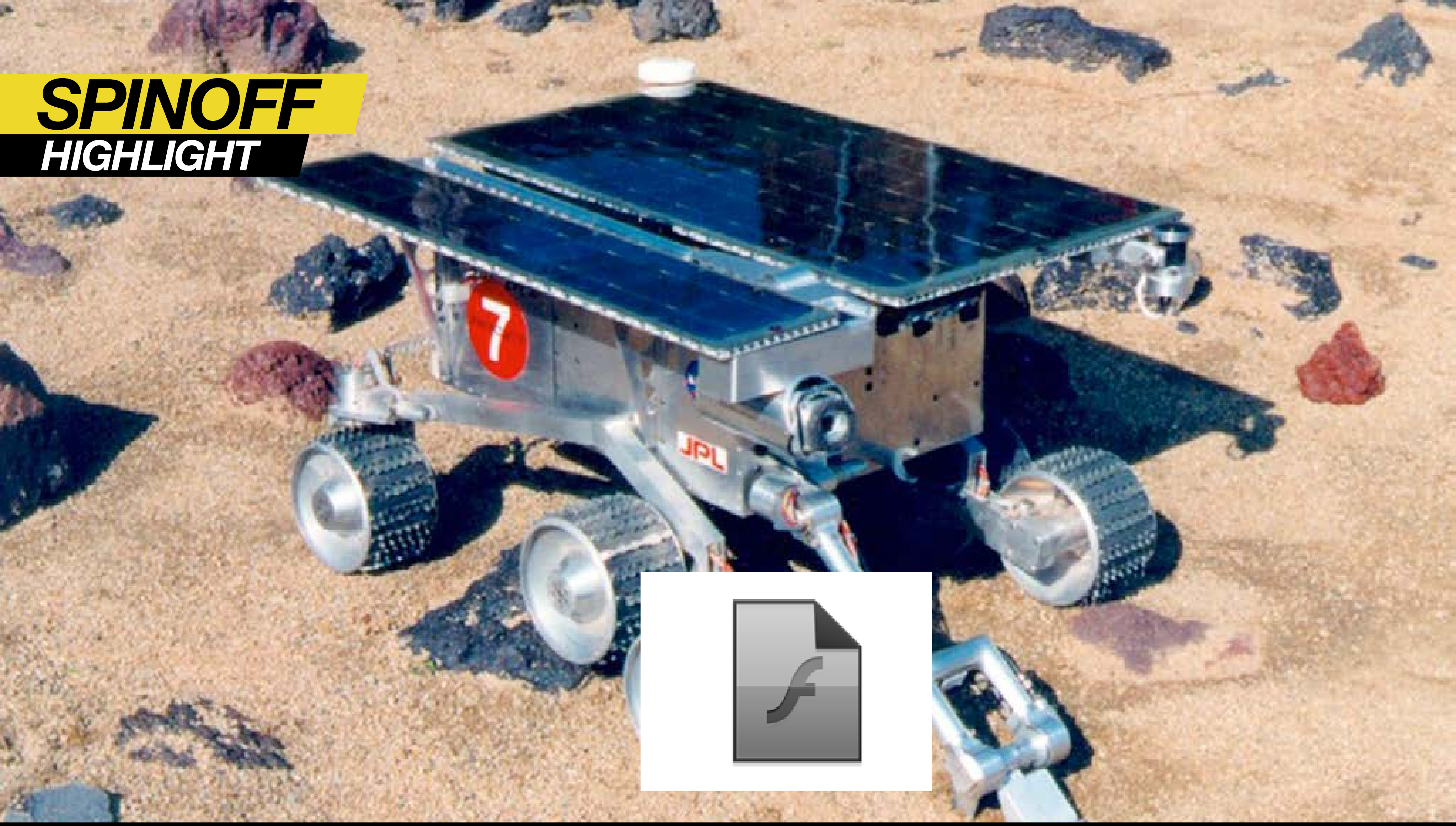
"It was a huge reward for us," said Yu Gu, team leader and an assistant professor in robotics at West Virginia University. "We started during the third year of the challenge and everything was new to us. We struggled to get things to work until the last few days, and we failed on the first trial. But we were so excited to see our robot finally complete Level 1. It was a memorable moment for everyone on the team."

It is NASA's hope that innovations stemming from this challenge will improve the Agency's capability to explore a variety of destinations in space, as well as enhance the Nation's robotic technology for use in industries and applications on Earth.

"This is a well-engineered challenge and the technology that all the teams are developing could benefit many future robot applications," said Gu. "This is not limited to planetary exploration, but also include areas such as disaster response, service and agriculture. NASA has been at the forefront of robotics research, and offering this challenge really shows NASA's leadership in this area."

The 2015 challenge will take place June 8–13 and will be live-streamed. More information can be found at ***www.nasa.gov/robot/*** and ***wp.wpi.edu/challenge/***.

SPINOFF HIGHLIGHT



BENEFITING BOTH MARS AND EARTH

A SPINOFF OF MARS TECHNOLOGY IMPROVING LOGISTICS IN HOSPITALS

Before the Curiosity Rover came Phoenix. Before Phoenix came the Mars Exploration Rovers, Spirit and Opportunity. Before Spirit and Opportunity came Pathfinder and Sojourner, the Mars Global Surveyor, and the Viking landers. Over the years, a host of Mars missions and programs have built on one another, spurring advancements in technology that have led to the impressive collection of Mars information and images we have today.

Between and during actual missions and programs, NASA scientists and engineers gain valuable knowledge and experience from research models, or prototypes, for future Mars missions. Rocky 7, one such prototype, was built at the Jet

Propulsion Laboratory (JPL) in the mid-1990s as a research test rover for navigation and sampling technology on Mars.

According to Richard Volpe, a robotics manager at JPL, the mechanical design of Rocky 7 allowed a system with fewer actuators, or motors. With fewer actuators needed for mobility, other actuators could be used for manipulation: a short sampling manipulator (an arm) and a long instrument manipulator (a mast). Rocky 7's arm could dig and collect small rocks and soil, while the mast had stereo cameras and the capability to hold an additional instrument, usually a microscopic imager.

[Paving the way for Mars Exploration Rover operations]

"The primary purpose of the mast was to provide images of the surrounding terrain from a high vantage point," Volpe says. "Using this capability in field tests in the Mojave Desert with Rocky 7, we demonstrated the operation style for a long-distance rover, paving the way for Mars Exploration Rover operations later."

ROBOTIC EVOLUTION

In the mid-1990s, JPL provided funding for the Vision and Touch Guided Manipulation group at the Massachusetts Institute of Technology's (MIT's) Artificial Intelligence (AI) Lab to develop object acquisition capabilities for robotic missions with a mounted arm like that on Rocky 7. MIT utilized two platforms for developing control capabilities to acquire rock samples: a Whole-Arm Manipulator (WAM) and a mockup of Rocky 7. At the time, Daniel Theobald was a graduate student working in the AI Lab, where he used the WAM to pick up rocks, present them to the camera, and then weigh and sort them into containers.

Theobald built the test system simulator for the mockup Rocky 7 system and used it to test the arm's capabilities. By 1999, Theobald had started working with Vecna Technologies in Cambridge, MA, where he applied the insights he had gained at the AI Lab. "I thought, if we can successfully have a robot operate on Mars for an extended period of time, then we should have robots on Earth, providing value on a daily basis," he says. "The robot autonomy system I developed for the Rocky 7 test platform acted as a starting point for the autonomy systems for Vecna's QC Bot," Theobald adds.

A MARS ROVER IN A HOSPITAL

According to Theobald, concep the QC Bot is a Mars rover in a ho "Like the Mars [Exploration] Ro must be able to operate robustl complex, unstructured environment away from the engineers who designed and built it," Theobald says.

To ease logistics in hospitals, QC Bot can be used for everything from delivering medications or taking out the trash, to ushering patients to their appointments. A configurable touch screen allows hospital staff and patients to interact with the robot through intuitive menus. The touch screen can be used for completing bedside registration as well as capturing vital signs. To achieve each of these tasks, the robot can autonomously call elevators and find its way through corridors.

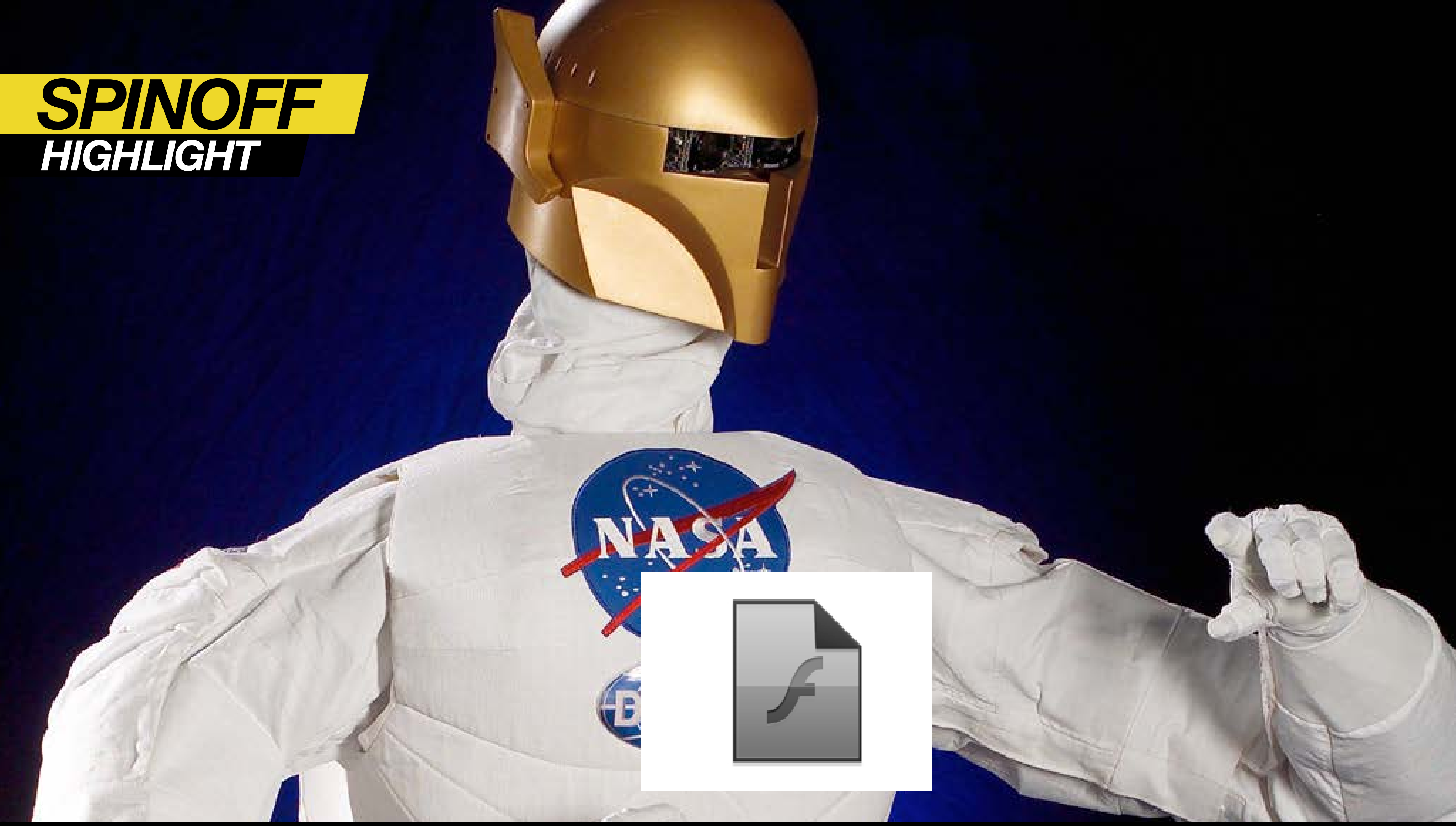
The robot's location can be communicated to hospital workstations, smartphones, or mobile devices, and doctors and nurses can call QC Bot to transport items like laundry, packages, or meals. Users can also place items in the robot's locking drawers, indicate the recipient, and then verify identities through biometrics, ID cards, or barcodes. If QC Bot encounters an unfamiliar obstacle in a facility, it will find a way around it or find a new route.

Currently, QC Bot is being used at a number of hospitals in the United States and internationally. Theobald believes the technology has the potential to improve efficiency, reduce medical errors, and increase patient and staff satisfaction.

“We really enjoy working with NASA to push the boundaries of human understanding while at the same time using that work to provide concrete benefit to daily life here on Earth,” Theobald says.

Before QC Bot came Rocky 7. What will QC Bot lead to?

QC Bot® is a registered trademark of Vecna Technologies.



ACTING, SENSING, REACTING, LEARNING

A SPINOFF SOFTWARE TEACHES MACHINES TO ADAPT AS THEY WORK, BENEFITING INDUSTRY

Autonomous robots helping astronauts sounds like a scene out of a science fiction movie. But in 1997, Johnson Space Center and the Defense Advanced Research Projects Agency (DARPA) engineers aimed to bring such a possibility closer to reality by building the humanoid Robonaut 1 to work alongside its human counterparts.

In order to be productive, Robonaut needed to be able to use the same tools as astronauts to service space flight hardware. Rob Ambrose, principal investigator for NASA's *Game Changing Development Program* and chief of the *Software, Robotics, and Simulation Division* at Johnson Space Center, says the majority of research at the time was focused on mobile robots that could avoid obstacles and drive over rough terrain. "There was a blind spot of sorts concerning manipulation," he adds. In addition, artificial intelligence was lacking that would enable robots to respond to unanticipated changes in their environment. This was a particular concern for the Robonaut engineers, because there can be delays or even failures in the communication between mission control and the International Space Station (ISS). Without commands, the robot would become useless.

[Without commands, the robot would become useless.]

SEEING IS LEARNING

In 2001, Johnson began seeking software for Robonaut 1 that could deliver automatic intelligence and learning. "We were looking for some simpler ways to teach robots and let them learn and internalize lessons on their own," says Ambrose.

Richard Alan Peters, a professor at Vanderbilt University, who was researching how mammals learn in order to write a learning program for robots, offered one approach. He observed that people use their senses to acquire information about their environment and then take certain actions. After identifying some common patterns, he incorporated them into learning algorithms that could be used with a robot.

Previous generations of artificial intelligence required pre- or hard programming of rules in order for the robot to determine how to respond. All the objects in an environment had to be labeled and classified before the robot could decide how to treat them. Peters aimed for software that could support robot autonomy by enabling the robot to sense a new object, determine its attributes, and decide how to best handle it.

By 2006, when the second generation Robonaut, R2, was built, the researchers "…took it to a new level and gave the robot the ability to reason about how to handle and interact with objects and tools," Ambrose explains. "The program is now running on Robonaut 2 in space," Ambrose adds.

Peters now serves as the chief technology officer at Universal Robotics, a software engineering company in Nashville, TN, where the NASA-derived technology is available in a product called Neocortex.

IMPROVING PRODUCTIVITY, ENHANCING SAFETY

Neocortex mimics the way peopl through the process of acting, se and reacting. Just like the part brain that Neocortex is named aft software provides insight into th or processes acquired through sensing. This sensing data is captured through actual sensors in cameras and lasers, or by other means.

According to Universal Robotics, Neocortex's ability to allow machines to adapt and react to variables and learn from experiences opens up process improvement opportunities for many Fortune 500 companies. It provides a new option in places where automation can impact efficiency and worker safety, such as in warehousing, mining, hazardous waste management, and vehicle use. The more Neocortex interacts with its environment, the smarter it becomes.

Hob Wubbena, vice president of Universal Robotics, says Neocortex can improve productivity by providing information that an employee cannot necessarily perceive, such as load balancing when stacking items. “Through the intelligence, new areas can be automated which contribute to safety as well as overall process efficiency,” Wubbena says.

While the innovations from Robonaut 1 are gradually improving life on the ISS, they are already benefiting life on Earth. “It’s really a tribute to NASA that a partnership was created with such a significant impact for the space program as well as business,” Wubbena says. “As we continue to help companies improve efficiency, quality and employee safety, we are proud to have worked with NASA.”

■

INSIGHT with

Kim Hambuchen

Robotics Engineer

Johnson Space Center

Kim Hambuchen says she "fell backwards" into robotics. College majors in biomedical, electrical, and computer engineering and an interest in image processing led to a computer vision class, where she learned about how robots could be programmed to see and learn. Her graduate education then led to a NASA fellowship that saw her join the Robonaut team at Johnson Space Center.

Now, leading the human-robot interface for the fifth-generation Robonaut, R5, Hambuchen has handled the remote operations of all the robots within the ***Robotics Systems and Technology Branch*** *of Johnson's* ***Software Robotics and Simulation Division****. This work has included the development of the* ***Robot Application Programming Interface Delegate (RAPID)*** *software, a system for controlling multiple, diverse robots that NASA now offers under an open source license. Below, Hambuchen shares her thoughts on the challenges of remotely operating robots, what NASA is doing to address those challenges, and what the future of space robotics holds.*

- **I came to NASA working with Robonaut as a graduate student** and used the work I was doing in perception-related applications to move into remote operation of our robots. Most of the robots we were working on at the time were intended to be controlled by people working on the Moon, but we also wanted to use them when there were no astronauts there, during unmanned spans. We started looking at ways to operate these robots with the 2- to 10-second round-trip time delay that we would get sending data between the Earth and the Moon. So, we built the Lunar Electric Rover, now called the *Multi-Mission Space Exploration Vehicle*, which we wanted to be able to control from Earth when there were no people on the Moon. **Figuring out how to teleoperate a robot with a 10-second round-trip time delay was very new** and there were only a few different methods out there.

[multi-Center robot communication system]

- Around that time, we started getting involved with the Jet Propulsion Laboratory (JPL) and the Ames Research Center doing this multi-Center project called *Desert RATS*. **We were trying to operate multiple robots from these different Centers using the same tools.** That led us to create RAPID, which is basically a multi-Center robot communication system. Over the years we've used RAPID to control the Centaur rover, which was the original Robonaut on a multiwheeled platform, the *Athlete* rover at JPL, and the *K10* rover at Ames. That was an experience because **it was bringing together different philosophies in robotics and different attitudes as to how to operate robots.** Over the course of that experience we learned a lot about controlling robots remotely. We even went to a 100-second round-trip time delay, which was basically like operating a Mars rover.

- The networks you have to use to get data to and from the robot are the first and foremost challenge. We use cameras on robots so the robot can "see" things, but it's not like seeing with human eyes. We need other sensors on the robots to give us depth perception. Those sensors produce a lot of data, more than we can think about pushing through the limited networks that we would expect on space missions. The biggest challenge with these sensors is giving the human operators situational awareness so they are not just relying on a tiny 2D image, as if someone took a funnel and put it in front of your eye. It's very difficult to get a good feel of what the terrain is like, how far away things are. **That's a huge challenge: How do you create an environment for the human operator that lets her know what is happening, what the environment is like, when you can only send back so much data?**

- Networks may have dropouts, and they may have time delays. **I call these "nasty networks."** You might not know what's going on at any given moment with your robot. You can only speculate and predict. Creating a system that keeps it safe and keeps it from harming anything else and harming itself is another huge challenge that requires a lot of autonomy on the part of the robot—it needs to be able to do things by itself without being commanded by a person. Operating space robotics, or doing remote operations with robots on the Moon or on an asteroid, is similar to operating robots that are underwater or robots that are on the other side of the world. There are many groups working on these problems, and we still haven't fully solved them.

- There is a big push in the robotics community to make robot control software open source. The school of thought is that we are not where we thought we would be with autonomous robots because everyone is basically reinventing the wheel. Everyone has his or her own method for avoiding obstacles with mobile robots, as well as his or her own method for attempting to grasp things with robot manipulators. By making the way you talk to the robot and the tools you use on the robot open source, people can start using those tools, and then they can start working on other things. **This open source movement in robotics is huge, and it's doing what we were hoping it would do.** People can start creating new algorithms and new processes. We specifically chose to do open source licensing with RAPID because we wanted anyone who wanted to put some software on one of our robots to have access to the communication system we're using, and to put any new tools they are using into the system.

[How much information is too much?]

- **At the end of the day, we're just trying to make robots to help humanity.**

- I took a few classes in cognitive science and psychology in graduate school. I was specifically researching ways to make robots pay attention to things in the same way a human would. For example, if a robot heard a sound that it didn't know, it would look in the direction of that sound to figure out what it was. Right now, we're using those fields of study to learn more about how people can control these robots. How much information is too much? How can we avoid overburdening a human operator but ensure that the robots have enough information to get the tasks done? We're in a spot right now with R5 where we're going back to cognitive science aspects and pulling those in for use with our operator system.

- **Fully autonomous robots are such a hard problem.** There is so much we don't know and can't make work very well. Having a human in the loop will be an end point for a while, but it is not the ultimate end goal. **What we learn**

from having a human in the loop is that the things we do to create a better situational awareness for the human operator simultaneously create better autonomy for the robot. Doing things for one will help the other.

- **What I see, especially at Johnson Space Center, is technology development, the combination of research plus application.** I want to shout it from the rooftops: We don't just do big, multimillion-dollar rockets. We do lots of smaller projects too, things that will get out into the world and make lives better.

- **The thing we really need to be able to advance is the perception system for the robots.** If you can't trust the sensory information that is coming back from the robot, you're still going to have a human hovering over the robot controls, waiting to punch the big red button. Perception systems for robots are still lacking 100 percent accuracy right now.

- While working with Robonaut as a student, the whole point was to make this robot that could go to the Space Station and do things that astronauts then wouldn't have to, thereby reducing the chances of an astronaut getting hit by micrometeorites, for example. Or, the robot could be sent to do things in place of humans on other planets, which would in fact be a much cheaper option. That idea really appealed to me; **I saw the potential for the future of robotics.**

- And the whole idea of maybe one day creating Rosie the Robot is just really cool. **Because I really don't like to clean my house.**

Bo Schwerin

June 15, 1977–December 22, 2014

We were deeply saddened to learn that Bo Schwerin, writer for *Technology Innovation*, passed away after a courageous 8-month battle with leukemia. Bo spent 7 years working at NASA, which included 5 years as a writer, and later editor-in-chief, of NASA's *Spinoff* publication. He was cherished by his colleagues for his creative mind and writing talent, as well as for his integrity, sincerity, and humility.

Bo is survived by his wife, Christine, and his son, Albert (Albee), who were the joys of his life.

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