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FOR THE
TECHNOLOGY
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MAY 2022

IEEE Spectrum

Underground With DARPA's SubT Challenge

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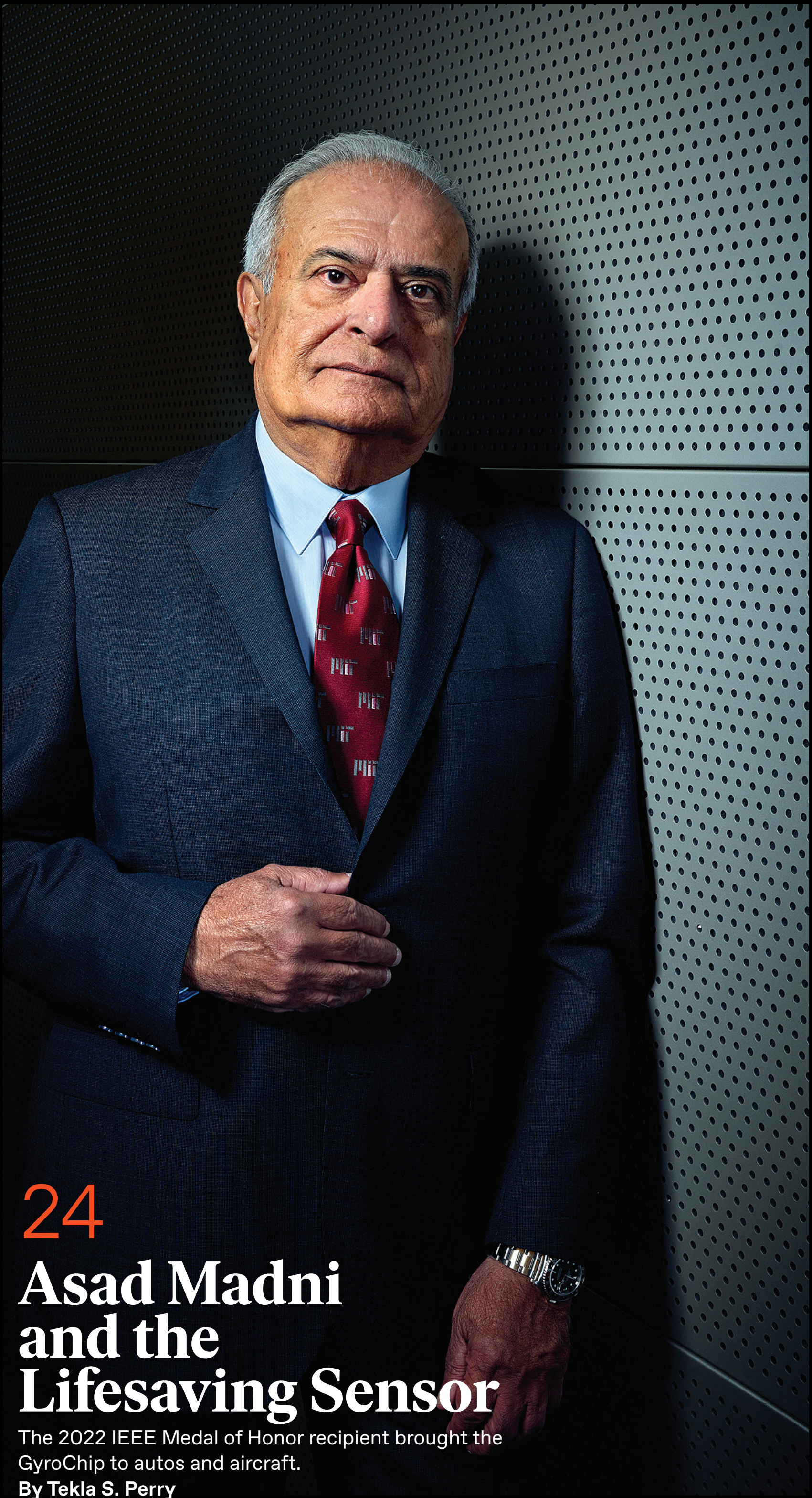

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EVAN ACKERMAN

BACK STORY

Underground With Robots

Travel was still considered a risk this past September when the DARPA Subterranean Challenge was scheduled to take place in Louisville, Ky. But after attending the preliminary rounds of the SubT Challenge in 2019 and 2020, senior editor Evan Ackerman was determined to make it to the final event in person.

Vaccinated, tested, and masked, Ackerman spent a week inside the Louisville Mega Cavern with the eight finalist teams and their robots. “Even though it was cold, dusty, and damp in the cave, the atmosphere was intensely exciting,” he recalls. Each team had its own garage area at one end of the cave, where they prepared a mix of ground robots and drones to navigate an underground course, collecting artifacts along the way. “It may have been a competition with millions of dollars on the line, but everyone was friendly and helpful,” Ackerman says. “Whenever a team would load up their robots and head off to the competition course, they’d leave to enthusiastic cheers and applause from all the other competitors.”

The course itself was kept secret. During the competition, DARPA allowed teams (and press) to see the course entrance and views from a few remote cameras, leaving much of the course a mystery. “We could only watch as teams sent their robots into the dark tunnel, one by one,” says Ackerman. “There’d be strange noises from deep inside the course. From time to time, DARPA would report that a point had been scored. When the clock ran out, the team would pack up and return to their garage, and DARPA staff would retrieve any robots that didn’t make it back.”

After the competition ended, DARPA opened the entire course up to experimentation, and Ackerman was invited to join Team Cerberus and Team CSIRO Data61 (which had placed first and second, respectively) as they wandered the course with some of their robots. “It was incredible,” says Ackerman. “DARPA had built an office, a warehouse, a multilevel subway station, and different kinds of natural caves, all from scratch. I’m only sorry that the course was temporary, and that more people weren’t given a chance to appreciate what DARPA created.”

For more on the competition and its impact on the future of robotics, see “Robots Conquer the Underground,” on p. 30. ■

CONTRIBUTORS

● ANTHONY F.J. LEVI

Levi is a professor of electrical and computer engineering at the University of Southern California. Gabriel Aeppli is head of the photon sciences division at the Paul Scherrer Institute, in Switzerland, as well as holding two professorships. The X-ray chip-scanning technology they describe on page 38 was born at what was "supposed to be a Sunday brunch between our families," says Levi. "But considering that we're Bell Labs alums, the conversation quickly turned to fundamental issues limiting progress in electronics."

● RAHUL RAO

Rao, a New York City–based journalist, has tackled a wide range of topics for a variety of publications, but for *IEEE Spectrum* he's focused on energy and energy policy. Rao, who writes about the Grand Ethiopian Renaissance Dam on page 10, has a long-standing interest in big infrastructure projects. "I think they're symbols of how the modern world can change people's lives," he says.

● VACLAV SMIL

Smil, a professor emeritus at the University of Manitoba, specializes in energy, but he also writes authoritatively on agriculture, food, invention, transportation, and East Asia. The common thread is his passion for quantification, thus the name of his monthly column, Numbers Don't Lie. On page 20, he examines the various estimates of the death toll from the COVID-19 pandemic.

● LAWRENCE ULRICH

Lawrence Ulrich is an award-winning automotive journalist based in New York City. In this issue, he writes about a company converting vintage Land Rovers to electric power [see "Tesla Inside," p. 44]. While this kind of thing is just "a game for wealthy people," he says, it reflects the automotive world's transition to electric power. One day electric 4×4s will be common, but for the moment, "you definitely end up with a vehicle that nobody else has."

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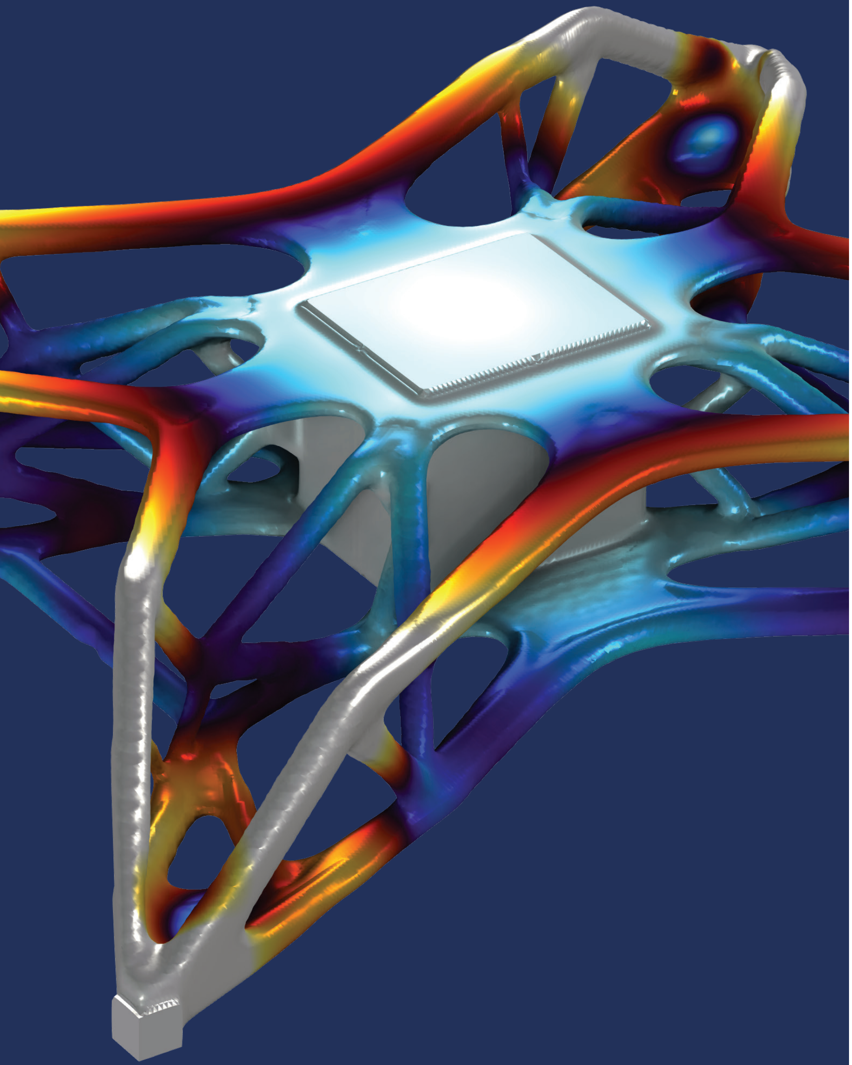

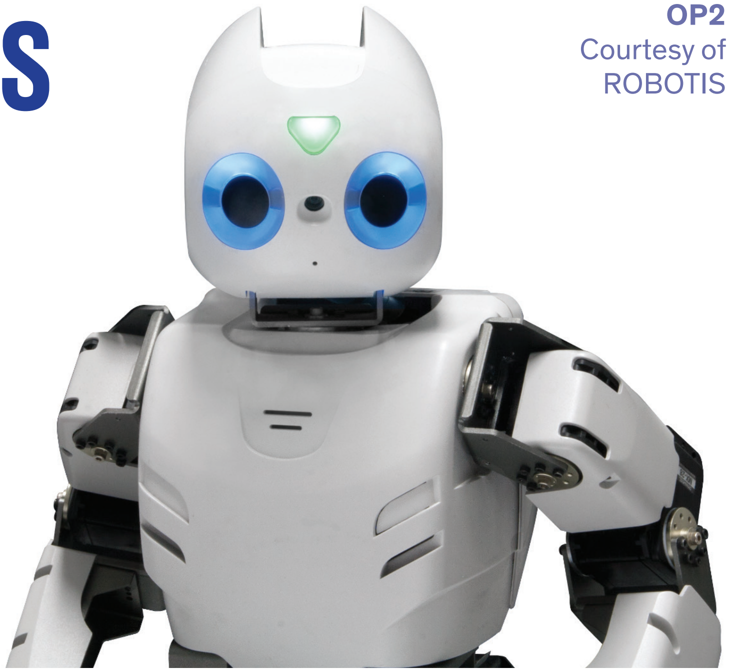

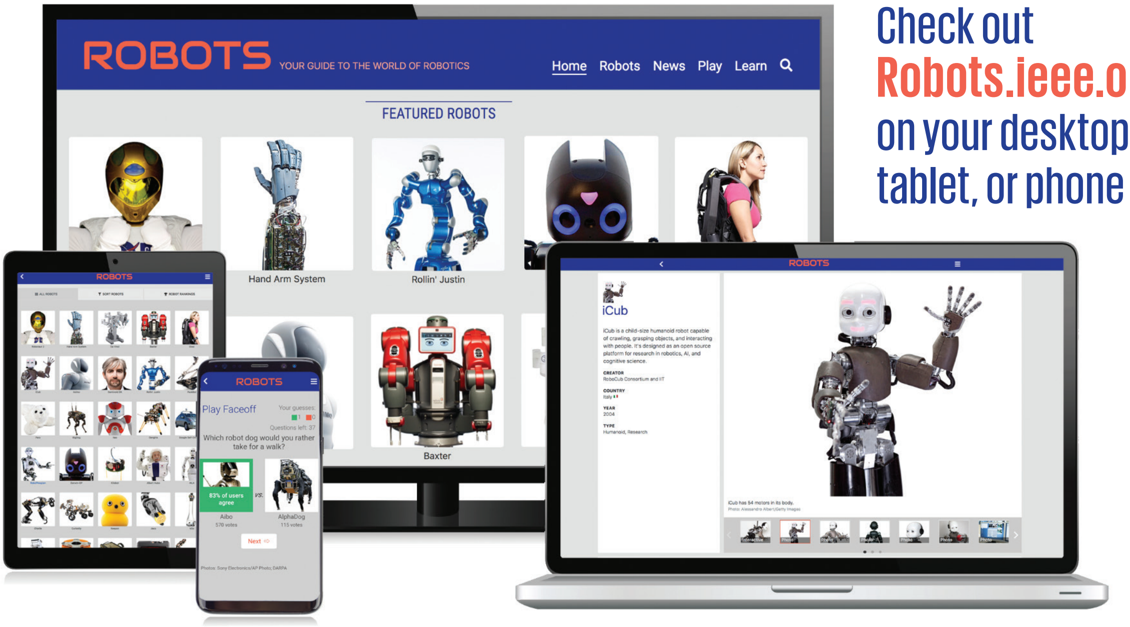

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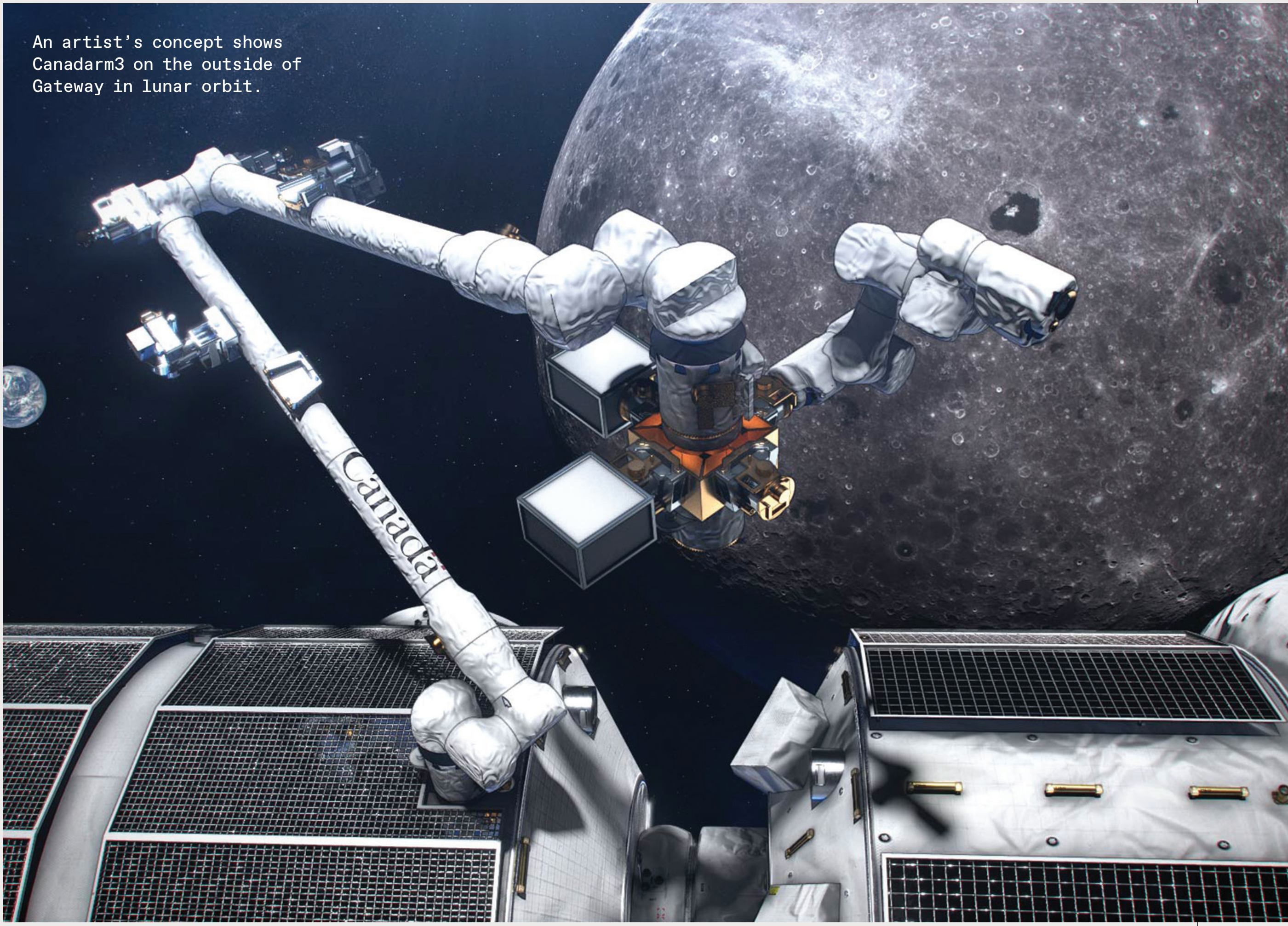


An artist's concept shows Canadarm3 on the outside of Gateway in lunar orbit.

CANADIAN SPACE AGENCY/NASA

ROBOTICS

Meet the Lunar Gateway's Robot Caretakers › With people seldom on board, the space station will rely on autonomy

BY EVAN ACKERMAN

An integral part of NASA's plan to return astronauts to the moon this decade is the Lunar Gateway, a space station that will be humanity's first permanent outpost outside of low Earth orbit. Gateway, a partnership between NASA, the Canadian Space Agency (CSA), the European Space Agency, and the Japan Aerospace Exploration Agency, is intended to support operations on the lunar surface while also serving as a staging point for exploration of Mars.

Gateway will be significantly smaller than the International Space Station (ISS), initially consisting of just two modules, with additional modules to be added over time. The first pieces of the station to reach lunar orbit will be the Power and Propulsion Element (PPE) attached to the Habitation and Logistics Outpost (HALO), scheduled to launch together on a SpaceX Falcon Heavy rocket in November 2024. The relatively small size of Gateway is possible because the station won't be crewed most of the time—astronauts may pass through for a few weeks, but the expectation is that Gateway will spend about 11 months out of the year without anyone on board.

This presents some unique challenges for Gateway. On the ISS, astronauts spend a substantial amount of time on station upkeep, but Gateway will have to keep itself functional for extended periods without any direct human assistance.

"The things that the crew does on the International Space Station will need to be handled by Gateway on its own," explains Julia Badger, Gateway autonomy system manager at NASA's Johnson Space Center. "There's also a big difference in the operational paradigm. Right now, ISS has a mission control that's full time. With Gateway, we're eventually expecting to have just 8 hours a week of ground operations." The hundreds of commands that the ISS receives every day to keep it running will still be necessary on Gateway—they'll just have to come from Gateway itself, rather than from humans back on Earth.

To make this possible, NASA is developing a vehicle system manager, or VSM, that will act somewhat like the omnipresent computer system found on virtually every science-fiction starship. The VSM will autonomously manage all of Gateway's functionality, taking care of any problems that come up to the extent that they can be managed with clever software and occasional input from a very far away human. "It's a new way of thinking compared to ISS," explains Badger. "If something breaks on Gateway, we either have to be able to live with it for a certain amount of time, or we've got to have the ability to remotely or autonomously fix it."

While Gateway itself can be thought of as a robot of sorts, there's a limited amount that can be reasonably and efficiently done through dedicated automated systems. NASA had to find a compromise between redundancy and both complexity and mass. For example, there was some discussion about whether Gateway's hatches should be able to open and close on their own, and NASA ultimately decided to leave the hatches manually operated. But that doesn't necessarily mean that Gateway won't be able to open its hatches without human assistance; it just means that there will be a need for robotic hands rather than human ones.

"I hope eventually we have robots up there that can open the hatches," Badger says. She explains that Gateway is being designed with potential intravehicular robots (IVRs) in mind, including things like adding visual markers to important locations, placing convenient charging ports around the station interior, and designing the hatches such that the force required to open them is compatible with the capabilities of robotic limbs. Parts of Gateway's systems may be modular as well; they can be removed and replaced by robots if necessary. "What we're trying to do," Badger explains, "is make smart choices about Gateway's design that don't add a lot of mass but will make it easier for a robot to work within the station."

NASA already has a substantial amount of experience with IVRs. Robonaut 2, a full-size humanoid robot, spent several years on the ISS starting in 2011, learning how to perform tasks that would otherwise have to be done by human astronauts. More recently, a trio of cubical, free-flying robots called Astrobees have taken up residence on the ISS, where they've been experimenting with autonomous sensing and navigation. A NASA project called ISAAC (Integrated System for Autonomous and Adaptive Caretaking) is now exploring how robots like Astrobee could be used for a variety of tasks on Gateway, from monitoring station health to autonomously transferring cargo. But in the near term, in Badger's opinion, "maintenance of Gateway, like using robots that can switch out broken components, is going to be more important than logistics types of tasks."

Badger believes that a combination of a generalized mobile manipulator like Robonaut 2 and a free flyer like Astrobee make for a good team, and this combination is currently the general concept for Gateway IVRs. This is not to say that the intravehicular robots that end up on Gateway will necessarily look like the robots that have been working on the ISS. But they'll be inspired by them, and will leverage all of the experience that NASA has gained with its robots on the ISS so far.

It might also be useful to have a limited number of specialized robots, Badger says. "For example, if there was a reason to get behind [an equipment] rack, you may want a snake type of robot for that."

While NASA is actively preparing for intravehicular robots on Gateway, such robots do not yet exist. The agency will not be building these robots itself, instead relying on industry partners to deliver designs that meet NASA's requirements. At launch, and likely for the first several years at least, Gateway will need to be able to take care of itself without internal


An astronaut holds Bumble, one of three Astrobee robots on the ISS.

JSC/NASA

Robonaut 2 prepares for manipulation tests in front of its task board on the ISS.

JSC/NASA

robotic assistants. However, one of the goals of Gateway is to operate completely autonomously for up to three weeks without any contact with Earth at all. The purpose is to mimic the three-week solar conjunction between Earth and Mars, in which the sun blocks any communications between the two planets. "I think that we will get IVR on board," Badger says. "If we really want Gateway to be able to take care of itself for 21 days, IVR is going to be a very important part of that. And having a robot is absolutely something that I think is going to be necessary as we move on to Mars."

Intravehicular robots are just half of the robotic team that will be necessary to keep Gateway running autonomously long-term. Space stations rely on complex external infrastructure for power, propulsion, thermal control, and much more. Since 2001, the ISS has been home to Canadarm2, a 17.6-meter robotic arm, which is able to move around the station to grapple and manipulate objects while under human control from either inside the station or from the ground.

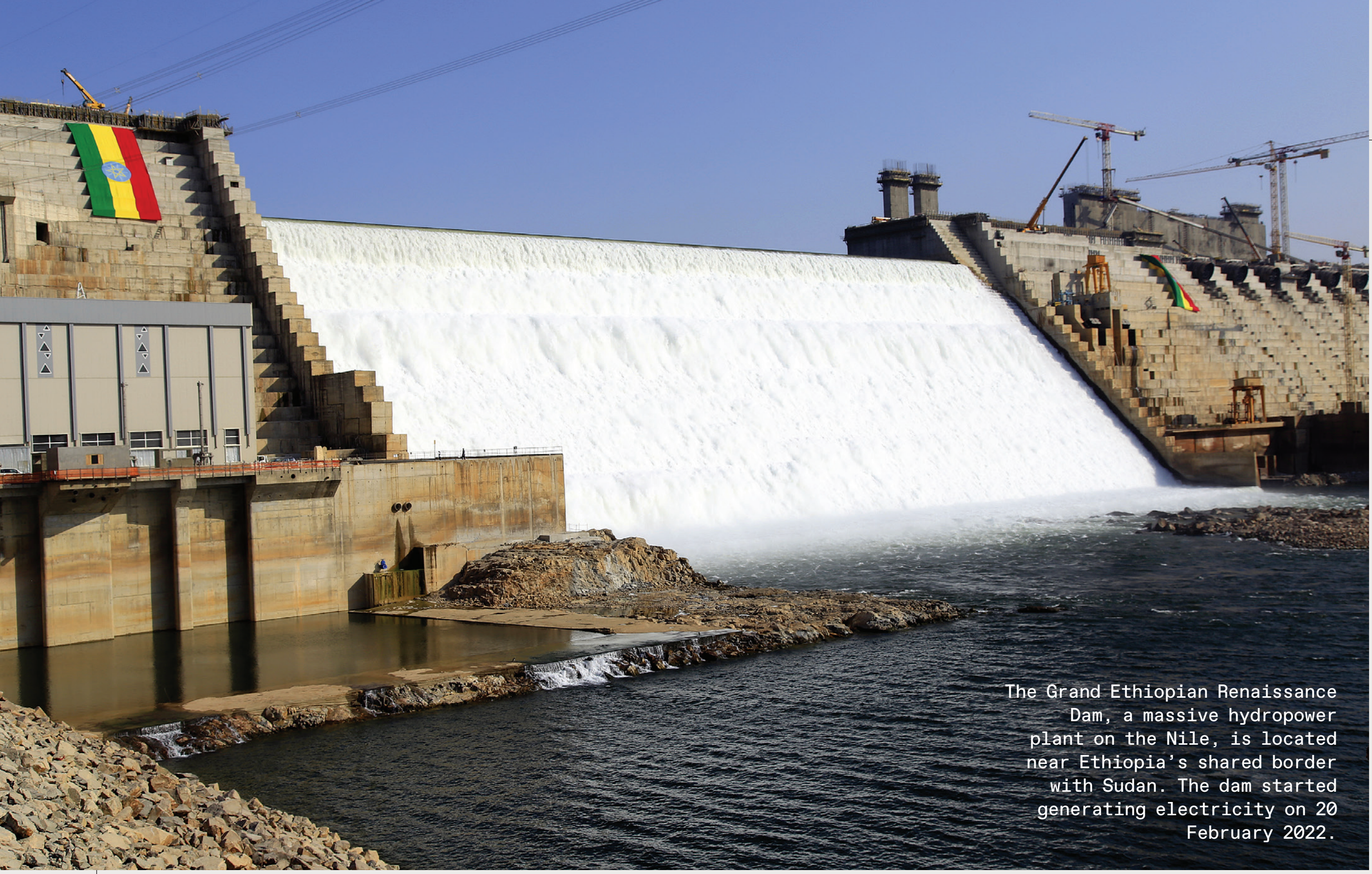
The CSA, in partnership with the Canadian company MDA, is developing a new robotic-arm system for Gateway called Canadarm3, scheduled to launch in 2026. Canadarm3 will include an 8.5-meter-long arm for grappling spacecraft and moving large objects, as well as a smaller, more dexterous robotic arm that can be used for delicate tasks. The smaller arm can even repair the larger arm if necessary. But what really sets Canadarm3 apart from its predecessors is how it's controlled, according to Daniel Rey, Gateway chief engineer and systems manager at the CSA. "One of the very novel things about Canadarm3 is its ability to operate autonomously, without any crew required," Rey says. This capability relies on a new generation of software and hardware that gives the arm the ability to react to stimuli.

Even though Gateway will be 1,000 times as far from Earth as the ISS, Rey explains that the added distance (about 400,000 kilometers) isn't what really necessitates Canadarm3's added autonomy. "Surprisingly, the location of Gateway in its orbit around the moon has a time delay to Earth that is not all that different from the time delays in low Earth orbit when you factor in various ground stations that signals have to pass through. With Canadarm3, we realize that if we want to get ready for Mars where that will no longer be the case, more autonomy will be required."

Canadarm3's autonomous tasks on Gateway will include external inspection, unloading logistics vehicles, deploying science payloads, and repairing Gateway by swapping damaged components with spares. Rey tells us that there will also be a science logistics airlock, with a moving table that can be used to pass equipment in and out of Gateway. "It'll be possible to deploy external science, or to bring external systems inside for repair, and for future internal robotic systems to cooperate with Canadarm3. I think that'll be a really exciting thing to see."

Even though it's going to take a couple of extra years for Gateway's robotic residents to arrive, the station will be operating mostly autonomously (by necessity) as soon as the Power and Propulsion Element and the Habitation and Logistics Outpost begin their journey to lunar orbit in November 2024. Several science payloads will be along for the ride, including heliophysics and space-weather experiments.

Gateway itself, though, is arguably the most important experiment of all. Its autonomous systems, whether embodied in internal and external robots or not, will be undergoing continual testing, and Gateway will need to prove itself before its technology is deemed trustworthy enough for deep-space travel. In addition to being able to operate for 21 days without communications, one of Gateway's eventual requirements is to be able to function for up to three years without any crew visits. This is the level of autonomy and reliability that we'll need, to be prepared for the exploration of Mars and beyond. ■



The Grand Ethiopian Renaissance Dam, a massive hydropower plant on the Nile, is located near Ethiopia’s shared border with Sudan. The dam started generating electricity on 20 February 2022.

ENERGY

East Africa’s Grand Dam Generates Strife › Doubling Ethiopia’s electricity supply threatens neighbors’ use of the Nile

BY RAHUL RAO

In the eyes of Ethiopia’s government, the future is a 145-meter-tall monument of rolled concrete and Francis turbines that spans the Blue Nile River within shouting distance of the Sudanese border.

That future shifted from vision to reality on 20 February, when Ethiopian prime minister Abiy Ahmed (a Nobel Peace Prize winner who has since come under fire for alleged war crimes in the country’s ongoing civil conflict) pressed a virtual button that turned on the Grand Ethiopian Renaissance Dam (GERD), by far Africa’s largest hydropower project to date.

That moment notwithstanding, the project isn’t complete just yet. The dam’s reservoir is still filling, and the full force of both its power and its downstream effects is yet to be seen. And when you zoom out, Ethiopian authorities’ lack of transparency about the whole project is only clouding its future.

The GERD project is truly monumental, and not just because the structure is taller than the Great Pyramid of Giza. When the dam is fully operational, its generating capacity will exceed 5,000 megawatts—enough, at least in theory, to double Ethiopia’s electricity supply.

So, it’s not hard to see why the Ethiopian government is keen on seeing the project through. Right now, less than half of the country’s population has access to electricity; most of Ethiopia’s energy comes from biomass, in the form of traditional sources such as firewood and animal dung. The use of those materials is linked to deforestation and respiratory illnesses.

Now, with the GERD operational, Ethiopia might fully electrify itself by the 2030s, without much fossil fuel in its energy mix.

MINASSE WONDIMU HAILU/ANADOLU AGENCY/GETTY IMAGES

To be sure, there has been progress in the nation's energy distribution program: Ethiopia's electrification has given an additional tenth of the country's population access to electricity since the Ethiopia Electrification Program kicked off in 2018. Most of that electricity comes from relatively clean hydropower; the country has considerable hydro potential, and it has begun to harness it with other dams such as Tekezé and Gilgel Gibe.

Now, with the GERD operational, Ethiopia might fully electrify itself by the 2030s, without much fossil fuel in its energy mix. There's even talk of selling power to neighboring countries—though the dam is located hundreds of kilometers from any major city, and it's not clear if Ethiopia's grid can handle the GERD's peak power, let alone transmit current to Sudan or Djibouti.

Before any of that happens, the 74-billion-cubic-meter reservoir in the dam's wake needs to fill up. Filling began in 2020, but the glass is still not even half full. It will be several more years before the reservoir fills up. As the reservoir level rises, it could eventually choke off the Blue Nile that feeds it, shutting off the flow that joins the Nile at the Sudanese capital of Khartoum.

The region's monsoon-driven climate will ultimately control how much water gets through. The throttle will be the amount of rain that falls during the wet season, between June and September. In 2021, for instance, the region saw more rain than average, minimizing the downstream effects.

But suppose the region is hit by drought; suppose Ethiopia closes the dam gates to force the reservoir to fill more quickly. Either, or both, could cut off the Blue Nile's flow and could impact hydropower plants like Sudan's 280-megawatt Roseires Dam and Egypt's 2,100-MW Aswan High Dam. "They have to think how to adapt the operation of the dam," says Hisham Eldardiry, an energy and water security researcher at Pacific Northwest National Laboratory, in Richland, Wash.

The Nile is much more than a hydropower resource. For millennia, people have relied on it for things like irrigating fields, and less water could harm environmentally sensitive breadbaskets downstream, such as the region around Khartoum and Egypt's Nile Delta. Farmers might be forced to avoid crops with high water needs. (Rice, for instance, could be eliminated as a crop.)

Eldardiry's research has found that the effects will be dependent on how long the reservoir takes to fill. If it's rapid (three or four years), then the downstream impacts will be more severe than if the Ethiopians slow down the filling (letting it crest in closer to seven years).

But Ethiopia isn't setting a firm target—at least not one that it's revealing publicly. For water managers downriver, that's a problem. "They need to know how much water is coming so they can plan ahead for the irrigation season or for the production of hydropower," says Eldardiry.

The dam's anticipated generation capacity has fluctuated a great deal over the years, from 6,500 MW down to 5,000 MW, amid criticism that those high numbers only described the peak capacity during the wettest part of the rainy season. The dam's Italian builders also allegedly conducted the dam's feasibility study, a potential conflict of interest.

Still, the GERD is a remarkable energy project in an especially deprived part of the Global South. Situated near an international border and directly impacting one of the world's major river systems, its situation is unique and delicate. But Eldardiry says that there are a few lessons it can teach planners of other hydropower projects.

For one, he says, it's important for governments to come together and reach agreements over resources—especially when it comes to projects like the GERD, whose effects ripple across multiple countries. "Reaching an agreement would have solved a lot of the problems," says Eldardiry.

Another takeaway: There are few things as important as what Ethiopia hasn't done—share data. ■

JOURNAL WATCH

Robots Rock What They Can't Roll

People around the world have long been captivated by the Moai, a collection of statues that stand sentry along the coast of Easter Island. The statues are well known not just for their immense size and distinct facial features, but also for the mystery that shrouds their geographic location. The question that piques everyone's curiosity is: How did ancient Rapa Nui people move these ginormous rocks—some weighing as much as 80 tonnes—across distances of up to 18 kilometers?

In 2011, a group of archaeologists made some progress in potentially unraveling this mystery. They conducted an experiment in which they tied three hemp ropes to the head of a Moai replica. Using two of the ropes angled at the sides to rock the statue back and forth and the third rope for guidance, they were able to "rock and walk" the replica forward. In the experiment, 18 people were able to move the 4.4-tonne replica 100 meters in just 40 minutes.

More recently, a group of researchers sought to use robots to employ this rock-and-walk technique further. Jungwon Seo, an assistant professor at the Hong Kong University of Science and Technology, and his team devised a rock-and-walk technique suitable for machines and implemented it four different ways. They describe their work in a study published 21 January in *IEEE Transactions on Robotics.*

In all the scenarios, the researchers used an object that had features like those of the Moai, such as a low center of gravity and a round edge along the bottom, which facilitate the dynamic rolling maneuvers. Seo foresees these rock-and-walk techniques being helpful when helicopters or other machines can't get the job done.

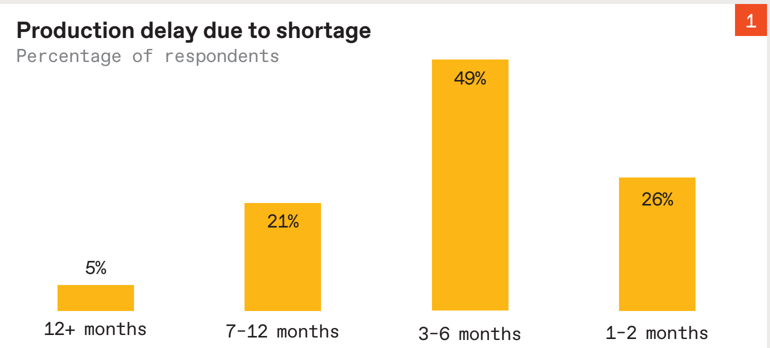
—Michelle Hampson

SEMICONDUCTORS

5 Ways the Chip Shortage Is Rewiring Tech

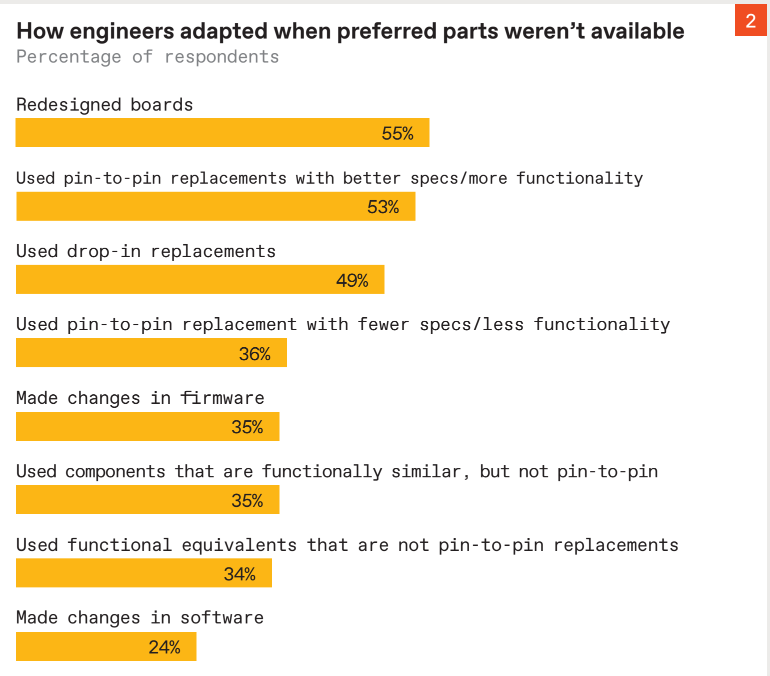
> Broken supply chains prompt companies to redesign products

BY JULIANNE PEPITONE


1

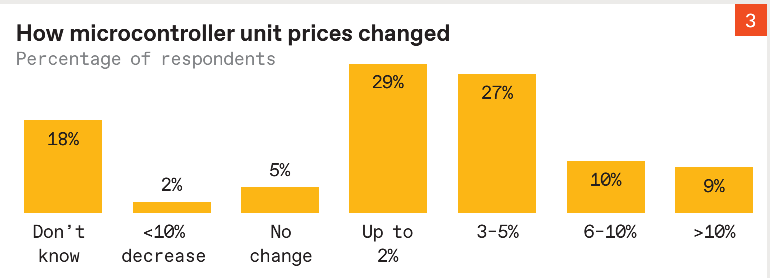
Production delay due to shortage

Percentage of respondents


2

How engineers adapted when preferred parts weren’t available

Percentage of respondents


3

How microcontroller unit prices changed

Percentage of respondents

SOURCE: AVNET

The global chip shortage’s effect on today’s products is clear in just about every consumer market in the developed world; it’s reflected in half-empty car dealership lots and shuttered manufacturing lines. COVID gets a lot of the blame—and it sure didn’t help—but the fact is, the disruption of the semiconductor market’s supply-demand balance has long been looming due to the proliferation of gadgets basic to everyday life.

The end of the shortage, unfortunately, is not near. Yuh-Jier Mii, R&D chief at the world’s largest contract chip manufacturer, Taiwan Semiconductor Manufacturing Co., recently told *IEEE Spectrum* that he believes it will take two to three years to get enough new chip fabrication facilities online to adequately address the shortfall.

So, the shortage isn’t just affecting the availability of today’s gadgets. The lack of chips is already fueling changes in the design of future products and delaying the next generations of devices. It is also forcing engineers to devise all manner of Plan Bs, according to a new survey from Avnet.

Sixty-four percent of the global engineers polled for the study say their companies are increasingly designing products based on the availability of components, rather than just following their preferences. This finding and others highlight how the chip shortage will alter technology—and tech jobs—for years to come.

“Just as [technologists] have had to think about manufacturability and testability, we need to start thinking about ‘procurability,’” says Samuel Russ, an associate professor of electrical engineering at the University of South Alabama. “It’s got to become part of the engineer’s lexicon, and we’ve got to figure out better ways to be more agile.”

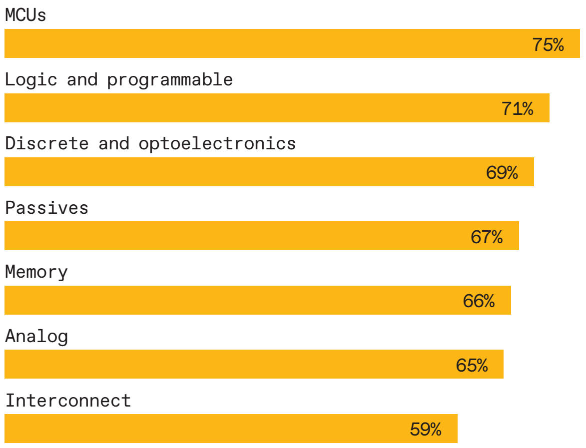
Russ stresses that tech workers shouldn’t view the crunch as a temporary problem to work around when designing. It’s a real-world component of the landscape that’s fundamentally altering how technologists, designers, and engineers work—and could become elemental to what tech is made, by whom, and when.

“In the past, design was separate from procurement. It was based on the technology—you pass it to the sourcing organization, you move that into production,” says Peggy Carrieres, Avnet’s vice president of global sales enablement and supplier development. These days, she says, “

4

Which category of components has been the most significantly impacted overall?

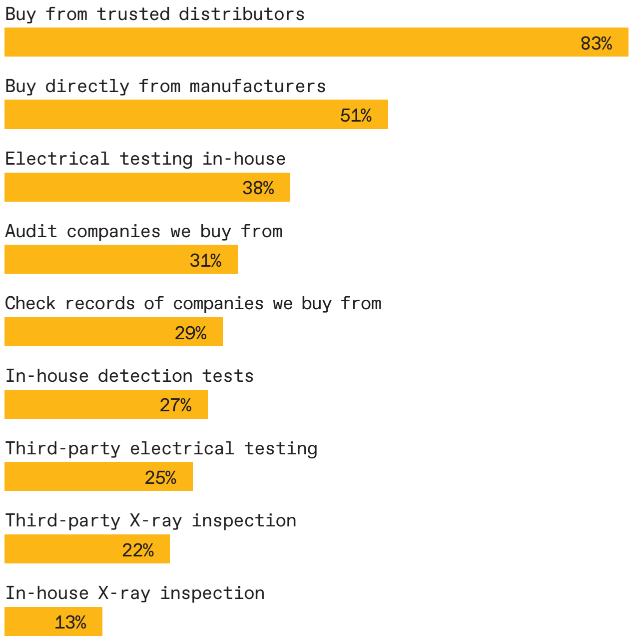
Percentage of respondents



5

How engineers are managing risk of counterfeit parts

Percentage of respondents



you have to think about [component] availability from day one."

Availability is particularly low for microcontrollers (a.k.a. microcontroller units, or MCUs), Avnet found (see Chart 4). Russ noted that unlike in the CPU world, which has Intel and AMD and then "scenery-chewing extras," the MCU space comprises a dozen different companies of roughly equal size. "The problem with MCUs is that it's not one or two parts; it's like 100 different parts that are low-volume products," Russ says. "So it's a lot harder to keep those in stock, especially if fab lines are starting to have to decide how to allocate. They're obviously going to want to focus on the high-volume stuff."

The supply-demand imbalance has helped to push MCU costs significantly higher, but that's not the only reason for price spikes. Also moving the needle, Carrieres notes, are macro factors affecting the economy at large: inflation, higher labor costs, intermittent shutdowns, and soaring prices for materials like palladium, which topped US $3,000 per ounce in March.

"It takes a while to rebalance that whole supply chain, and we've got these megatrends happening," Carrieres adds. "There's ever more demand, and the cost to manufacture has gone up, so that has to be reflected in the selling price."

Engineers are being forced into "behavioral" changes when it comes to design and product-generation road maps, Carrieres says: "They're delaying the next-gen projects and extending the marketing cycles for products already in production, because they may have already [worked out the sourcing for] the mix of materials for that previous production. It's pushing out the addition of new innovations—or forcing the removal of features in the current production cycle—because they've got to focus on, 'Well, what do we have available to build?'"

Design engineers have limited alternatives when faced with so many headwinds. "None of the options are great—if you can find a pin-to-pin replacement, that's the easiest. But that may or may not be possible," Russ says. "You've either got to redesign the board or come up with some kind of adapter. You have to start making those considerations: How easily can the board be redesigned? How high is the volume of production for your board?"

Russ adds: "In a situation like this, where the industry is throwing you curveballs, you have to have a 360-degree view of your product. Is it manufacturable? Is it procurable? What does it do to the cost? What does it do to the performance? [Tech designers and engineers] especially have got to keep the procurement organization and the manufacturing organization on speed dial."

While engineers have always needed a strategic view to some extent, Carrieres notes that "the forces that are at play today are so much more complex. So, when you start your design, even from the first sketch, [you have to] look beyond the board. It's tempting to go deep into that design and stay focused on the technology, but you have to look beyond the board in order to ultimately be successful." ■

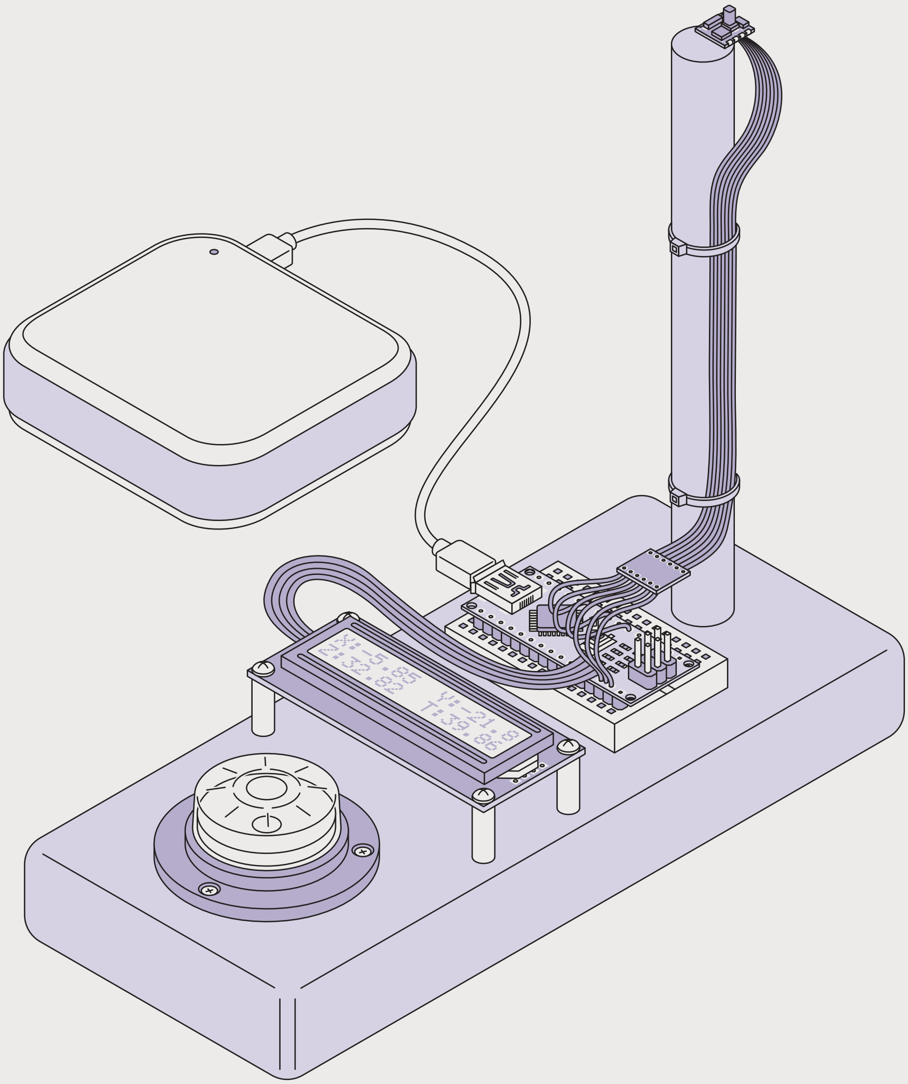
A Roomba for Rivers

By Willie D. Jones

Humankind is enamored with water. The beauty and utility of Earth's oceans, rivers, lakes, and streams explain why 40 percent of us live within 100 kilometers of the planet's coastlines. But we don't always respect and properly care for the things we love. As with many of our habitats, the world's waterways have become dumping grounds for our trash. Picking up the litter that fouls these otherwise picturesque areas is a full-time job. But few localities have the resources or political will to pay for cleanup costs. That might change now that French robotics company Interactive Autonomous Dynamic Systems (IADYS) has introduced the Jellyfishbot. The machine, which can run autonomously or at the direction of a remote operator, goes around collecting the junk and gunk (like plastic bottles, oil spills, and algae) that float on the water, as well as detritus located up to 10 meters below the surface. The Jellyfishbot is studded with sensors that allow it to navigate autonomously. The sensors also measure the quality of the water in terms of salinity, temperature, turbidity, and the proliferation of organisms, including cyanobacteria and phytoplankton. Hooray for robot labor!

PHOTOGRAPH BY SEBASTIAN GOLLNOW/PICTURE ALLIANCE/GETTY IMAGES

Hands On



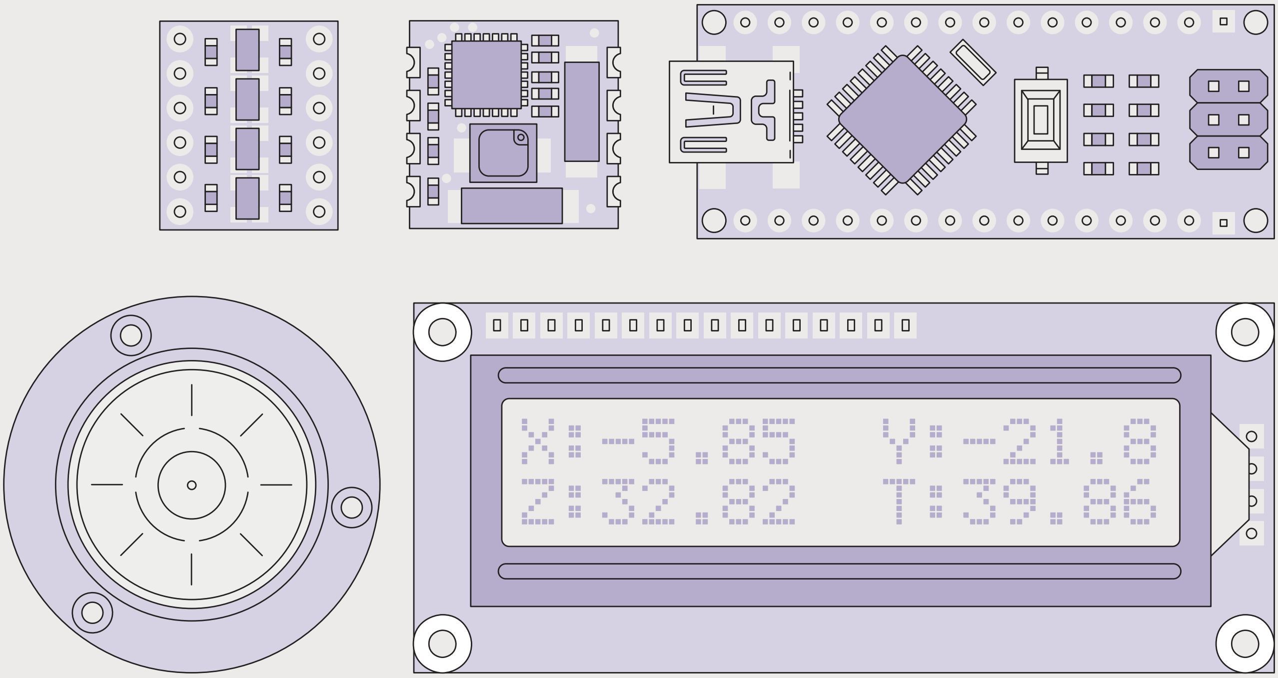
This DIY magnetometer uses an RM3100 3-axis sensor board, which is physically separated from the other components by about 30 centimeters to avoid having those other components affect the magnetic field that is measured.

DIY Magnetometer › Search for buried treasure for less than $100

DAVID SCHNEIDER

In the 1968 movie *2001: A Space Odyssey*, an oddness in the moon's magnetic field leads scientists to an alien monolith buried under Tycho crater. The notion of being led to a hidden object by virtue of the magnetic anomaly it creates must have really intrigued my 9-year-old self, because a decade after seeing that movie I decided to build a circuit to measure the strength of Earth's magnetic field. So I read some World War II–era journal articles and learned about the magnetometers used to locate sub-

Illustrations by James Provost



The project involves [clockwise from top left] four small and inexpensive circuit boards—a level shifter, an RM3100 sensor, an Arduino Nano, and an LCD display—along with a bull's-eye level.

merged German submarines. With that information, I constructed what's called a fluxgate magnetometer. It was crude, but it worked.

I was reminded of that project by a recent *IEEE Spectrum* feature about magnetic amplifiers, which rely on metal alloys that become highly magnetized in the presence of a magnetic field. These alloys tend to saturate, meaning that they cannot become further magnetized as the field increases. Magnetic amplifiers and fluxgate magnetometers both make use of this phenomenon.

That jog down memory lane led me to read about a different type of magnetic-field sensor that also relies on such alloys, called a magneto-inductive magnetometer, which appears to have first been commercialized around 2010. This magnetic-field sensor is surprisingly simple, so I headed to the garage to see whether I could build this type of magnetometer just with stuff I had on hand.

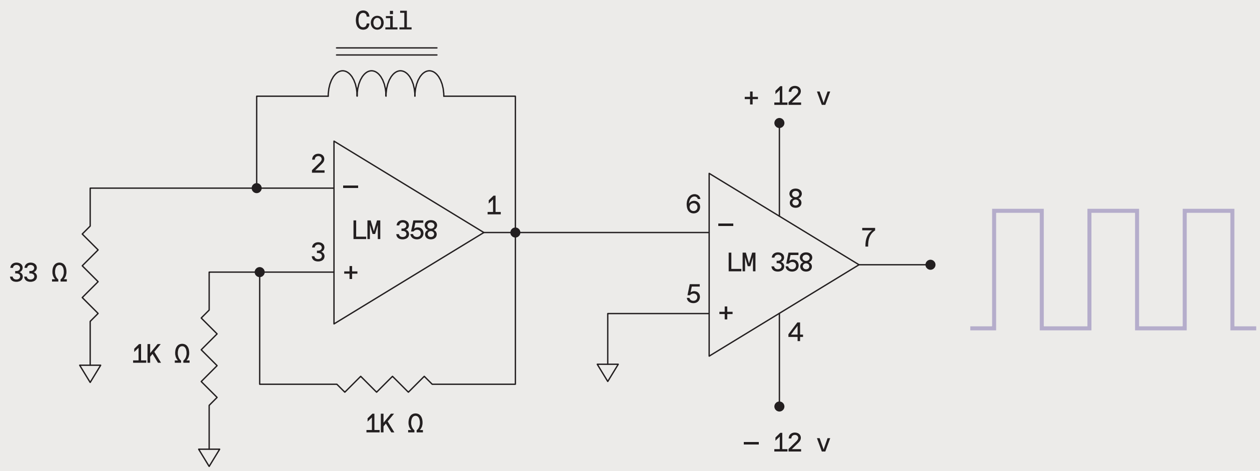
Amazingly, I managed to locate a tattered envelope containing pieces of the magnetic alloy (Mu-metal) that I had used decades ago to build a fluxgate magnetometer. And that was the only hard-to-obtain item I needed.

I scrounged a 6-millimeter-diameter plastic tube, which I put into the chuck of an electric drill and wound a few hundred turns of 32-gauge magnet wire around it. I then stuffed five slender pieces of Mu-metal into the tube.

In addition to this coil, my homebrew magneto-inductive sensor required just three resistors and one LM358 chip, which contains two op amps. One op amp is wired to two resistors to form an inverting Schmitt trigger: a comparator with two different voltage thresholds. When the input voltage rises past one threshold, the output switches negative; when the input falls below the second, lower threshold, the output switches positive. The third resistor is attached to the trigger's input, with the coil providing feedback.

This arrangement [following page] creates a relaxation oscillator, the output of which looks quite funky on an oscilloscope. But feeding it to a second op amp configured as a simple comparator (one that compares the input with zero volts) squared the signal up nicely, with the output switching between the +12-volt and −12-volt supply rails every 3 milliseconds or so.

The exact shape of this square wave depends on the changing inductance of the coil, which varies during each oscillation because the magnetic field applied to the coil's Mu-metal core varies. The Mu-metal is also affected by external magnetic fields. So when the coil is pointed north (and downward, at my northern latitude), the Earth's magnetic field adds to the magnetic field created by positive currents in the coil windings; when



You can construct a very basic magneto-inductive sensor using just two op amps, three resistors, and a coil that is wound around a Mu-metal core. The duty cycle of the square-wave output depends on the magnetic field to which the coil is subjected.

pointed in the opposite direction, the Earth's field subtracts.

As a result, the duty cycle of this little square-wave oscillator changes: Point one end of the coil in the direction of Earth's field and the time spent at +12 volts gets longer while the time spent at −12 volts gets shorter. Rotate the coil by 180 degrees, and the opposite changes occur.

After satisfying myself that this homebrew magneto-inductive sensor actually worked, I decided to see what I could do with a commercial unit that contains three sensors of this type. It can be purchased on Amazon for just US $40.

I connected this RM3100 sensor board to an Arduino Nano through a Serial Peripheral Interface (SPI), using code posted on GitHub late last year by the manufacturer, PNI Sensor Corp. The values it produced seemed reasonable for my location—about 40 microteslas—so I added an LCD display and mounted the sensor board about 30 centimeters from the other components so as to minimize their influence on the field measurements. I also added a bull's-eye level, which I figured would be useful for measuring the vertical component of the magnetic field. Power comes from an external USB battery.

Short-term stability didn't quite match what's advertised in the manufacturer's literature, perhaps because of electrical noise in the environment, but it's still very good: With the unit motionless, the values shown remain within a few tens of nanoteslas. But the total field calculated from the *x*, *y*, *z* components varies considerably with the orientation of the sensor. That probably reflects the influence of one sensor coil on the others, as another experimenter has concluded. And this would surely prove problematic using this device on the move.

Hunting for submarines during the Second World War using fluxgate magnetometers involved a similar challenge—how to determine the total magnetic field using vector sensors, which measure *x*, *y*, *z* components. Those sub hunters needed to track the total field because a single component would vary erratically just from physical motions. If the three orthogonal sensors were independent and perfectly calibrated, and if you had digital values and a computer to apply the Pythagorean theorem, no big deal. But all that wasn't available in the 1940s.

The solution these sub hunters arrived at was to mount their magnetometers on a gimbaled platform, using the output of two of the sensors to drive motors that reoriented the magnetometer so that the third sensor would always be pointed along the magnetic field. The third sensor would thus track the total-field value. I found I could do something similar by hand, orienting my device in a direction that zeroed out the *x* and *y* outputs, leaving *z* to show the total field.

In addition to a coil with a Mu-metal core, my homebrew magneto-inductive sensor required just three resistors and one LM358 chip, which contains two op amps.

I've not used my DIY magnetometer to search for any submarines or alien monoliths, but I did test it using a steel hammer, which affects the readings in an obvious way when placed within about a meter of the sensor board. In a real search, though, what you can detect will depend on how much the magnetic background varies.

I suppose a magnetometer like this could be used to locate shipwrecks or find an old car buried under your garden—it happens! My plan for it is to try to map some interesting geologic structures in my area, where finding a highly magnetizable type of rock sometimes proves valuable to homeowners because it makes for a good place to drill a water well. ■

Careers

JOHN UNDERWOOD/PURDUE UNIVERSITY

How Purdue University Commercializes Its Research

› Yung-Hsiang Lu helps turn research results into revenue

BY DANIEL P. DERN

For Yung-Hsiang Lu, improving the energy efficiency of computer technology to provide real-world benefits has been a lifelong focus.

"When I was learning data structures, I began to see things from a different viewpoint—how to make things efficient," says Lu, a professor of electrical and computer engineering and a university faculty scholar at Purdue University's Elmore Family School of Electrical and Computer Engineering, in West Lafayette, Ind.

The IEEE Fellow's research focuses on developing energy-efficient computing systems. Improved efficiency is increasingly essential for tasks like computer vision and imaging activities. It is particularly critical where battery weight, size, and capacity is a precious resource, such as in small and mobile devices like distributed sensor networks, autonomous robots, wireless communication, and real-time systems.

Over the past several years, his research has included collecting and analyzing data from networked cameras in department stores, optimizing how they place their products, and assessing COVID-19 lockdown compliance based on multinational camera data.

Lu is also guiding the next generation of researchers—both graduate and undergraduate students.

"I used to think I just wanted to write research papers," Lu says. But after several of his students won the 2014 Schurz Innovation Challenge at Purdue, where students presented concepts for Web and mobile applications, Lu says he wanted to help students go from "research to technology transfer and commercialization. I want to see research results get used in the real world.

"I still do research, of course," Lu notes. "In fact, I received three research grants last year."

Lu has written several books, and in 2015 he became a principal investigator for the U.S. National Science Foundation's Innovation Corps (I-Corps) program, which helps NSF-supported professors understand the commercial value of their research.

That same year, Lu helped start the now-international IEEE Low-Power Computer Vision Challenge, an annual competition that aims to improve the energy efficiency of computer vision (CV) for running on systems with stringent resource constraints. Computer vision, Lu says, "remains one of the grand challenges in AI. To date, the competition has received more than 500 solutions for CV problems from over 100 teams around the world."

He has also been involved in several technology challenge events. He is one of the organizers of this year's IEEE Autonomous Unmanned Aerial Vehicles (UAV) Competition, which challenges teams to see which of their UAVs can successfully follow a moving target without a teleoperator.

Lu was appointed the inaugural director of Purdue's John Martinson Entrepreneurial Center in 2020. It is one of many entrepreneurial programs and activities at the school. In 2021, he was named the first Innovation and Entrepreneurship Fellow for the College of Engineering.

One observation Lu says he made during the I-Corps program is that "the problems people in the real world face may not be the ones we at universities imagined." He says it's important for researchers to talk with people outside of academia because "they look at things differently."

Lu also encourages students to try to get involved in a project that lasts more than one semester.

"When you are working on a one-semester project, it's so short you don't think about consequences for bad decisions," he says. "If you are in a project for one year, a lot of bad decisions will come back and hurt you, which you learn from." ■

Crosstalk

COVID: Excess Mortalities Two Years Later

The death toll is increasingly comparable to that of the 1918–1920 flu

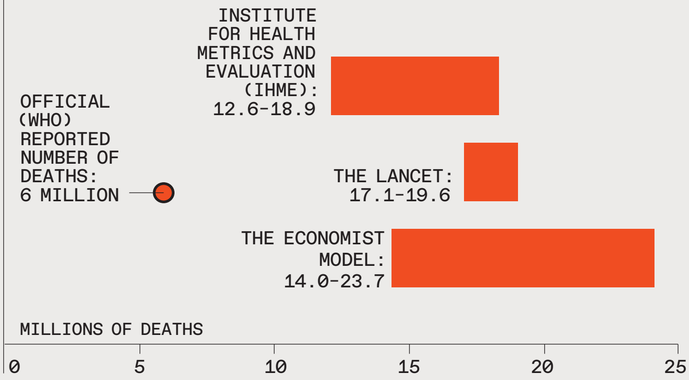
The World Health Organization (WHO) declared the outbreak of the COVID-19 pandemic on 11 March 2020. Two years later, it put the cumulative number of cases at about 452 million, more than 5 percent of the world's population, and the number of new infections was still averaging more than a million a day.

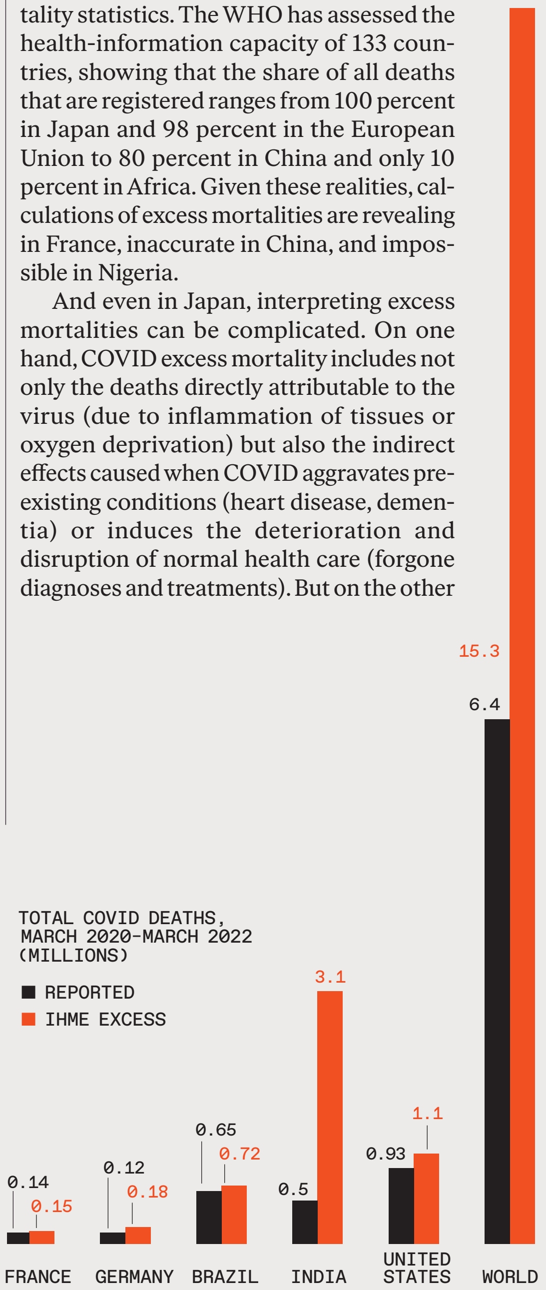
How many people have died? We can begin to model the problem by using the highest mortality estimates of the two previous major pandemics—138 deaths per 100,000 people in 1957–1958 and 111 per 100,000 in 1968–1969. A similarly virulent two-year event, adjusted for today's population of 7.9 billion, would then be expected to kill 8.8–10 million people. On 11 March 2022, the WHO's officially logged COVID death toll was about 6 million. Every epidemiologist knows that this must be a significant underestimate.

Estimates of actual global mortality attributable to COVID are at least two and up to four times as much as the officially reported total.

A better way to assess the death toll is to calculate excess mortality: that is, the difference between the total number of deaths during a crisis and the deaths that would be expected under normal conditions. Obviously, this approach will work only in those countries that collect near-impeccable mortality statistics. The WHO has assessed the health-information capacity of 133 countries, showing that the share of all deaths that are registered ranges from 100 percent in Japan and 98 percent in the European Union to 80 percent in China and only 10 percent in Africa. Given these realities, calculations of excess mortalities are revealing in France, inaccurate in China, and impossible in Nigeria.

And even in Japan, interpreting excess mortalities can be complicated. On one hand, COVID excess mortality includes not only the deaths directly attributable to the virus (due to inflammation of tissues or oxygen deprivation) but also the indirect effects caused when COVID aggravates preexisting conditions (heart disease, dementia) or induces the deterioration and disruption of normal health care (forgone diagnoses and treatments). But on the other




TOTAL COVID DEATHS, MARCH 2020–MARCH 2022 (MILLIONS)

SOURCES: WHO, IHME, THE LANCET, THE ECONOMIST. THE NUMBERS FROM THE WHO ARE REPORTED DEATHS. ALL OTHERS ARE ESTIMATES.

hand, the spread of COVID appears to have largely preempted seasonal excess mortality caused by winter flu epidemics among the elderly, and lockdowns and economic slowdowns improved the quality of outdoor air.

By the end of 2020 the official worldwide COVID death toll was 1.91 million, but the WHO's preliminary evaluation estimated at least 3 million deaths. According to Seattle's Institute for Health Metrics and Evaluation (IHME), which counts only cases caused directly by the virus, not by the pandemic's disruption of health care, excess global mortality reached 15.34 million (that is, between 12.6 and 18.9 million) by 11 March 2022. That's the second anniversary of the beginning of the pandemic, according to the WHO's reckoning.

A model run by *The Economist* relies on scores of national indicators correlating with data on excess death and thus it has produced a wide range of estimates. For the pandemic's two-year mark, the range is between 14 million (more than 2 times the official tally of 6 million) and 23.7 million (nearly 4 times the official number), with the central value at 20 million (3.3 times the official total). And on 10 March 2022, *The Lancet*, one of the world's leading medical journals, published its excess mortality estimate for 2020 and 2021: 18.2 (17.1 to 19.6) mil9lion, nearly 3.1 times the official two-year tally.

Even using a toll of around 15 million deaths is enough to put COVID-19 far ahead of the two major post-1945 pandemics on a per capita basis. And any number above 20 million would make it in absolute terms (but not in relation to population) an event on the same order of magnitude as the great 1918–1920 influenza pandemic. Will we ever know the real toll to within 10 percent, plus or minus? ■

The officially logged COVID death toll is about 6 million; every epidemiologist knows that this must be a significant underestimate.

MYTH AND MACHINE BY RODNEY BROOKS

How Networks Catalyze Civilization

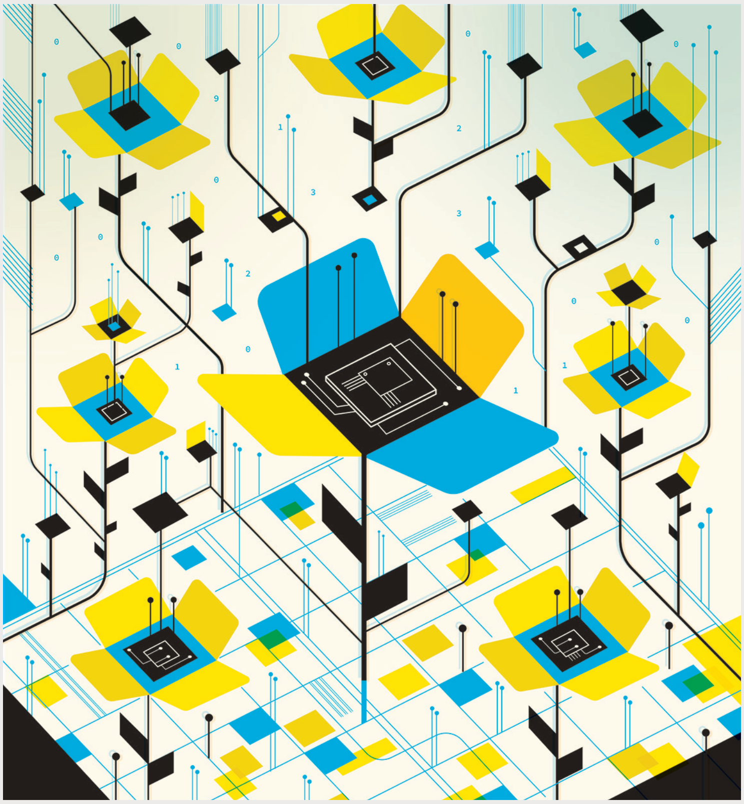
A minor miracle called autocatalysis sustains organisms and vast communications networks

PORTRAITS BY SERGIO ALBIAC

Thanks to the catalytic converter in their cars, most people have an idea of what catalysis is. It refers to a chemical reaction that is enabled, or greatly speeded up, by the presence of one or more other chemicals. A catalytic converter, for example, uses palladium, rhodium, and platinum to convert pollutants like carbon monoxide, nitric oxide, and nitrogen dioxide into water and carbon dioxide.

More than 90 percent of all industrial-chemical processes depend on catalysis. But for living systems, a more important phenomenon is autocatalysis, in which one of the chemical products of a reaction is itself a catalyst for that same reaction. Think of it as a feature that, under the right conditions, allows a chemical reaction to amplify itself.

It is a stunningly powerful mechanism. Life itself depends on autocatalytic chemical reactions—beneath our placid exteriors we are a seething mass of autocatalysis. Remarkably, this same concept, of a system giving rise to a factor that then synergistically enlarges or improves the system, can often be seen in the networks created by human beings. It's true of social networks, transportation networks, commercial networks, and, especially, communication networks.



In the 18th century, Great Britain built a network of canals that enabled, rather suddenly, the delivery of raw materials, coal for power, and access to ports for the finished goods. That, in turn, led to the invention of factories, which set the stage for the Industrial Revolution. Of course, the explosion of industrial activity that ensued was very, very good for the canal network. Here, the factories were the catalyst, spawned by the canal-network system that they then expanded and strengthened.

Fast-forward roughly 250 years, to the 1980s, in the United States. We have various electronic communication networks (the autocatalytic system) and some early personal computers (the catalyst). Personal computers are not yet ubiquitous, but then, in 1989, along comes the Internet, a second generation of a packet-data network that had started out as a communications network for the military and for sharing scarce computer resources in academia. Because the Internet was available to any customer who wanted to pay, the demand for network bandwidth surged and set the stage for the World Wide Web, an easy-to-use information network overlaid on the packet-data network. At last, people had a compelling reason to buy a computer.

The Web soon became a vehicle for commerce, and demand rose even more. Ultimately, we needed to build large data centers as the back end of that commerce system. Then a bunch of folks got the brilliant idea to offer businesses the computational resources, in addition to the storage, of those data centers. Thus, cloud computing was born.

Years later, cloud computing enabled the large-scale training needed for deep neural networks. The computational demands for this training are now so great that they are driving the growth of cloud-computing networks, which are fed by a worldwide network of mostly low-paid piece workers in the developing world who label data needed to keep the training going. They use the Web to move the data around, and to get paid.

Are we in the endgame for deep neural networks? Or will we manage to get past the very narrow capabilities of today's deep-learning networks to new AI technologies? And if we do, will there be new networks that arise and are autocatalytic with this new form of AI, whatever it might be?

Some researchers, engineers, and entrepreneurs are probably peering through the fog of the immediate and starting to see how new autocatalytic processes will interact. Some of them will start vastly successful companies. I don't know exactly what those companies will do; if I did, I would start one myself. But I have a couple of ideas.

COVID-19 quickened the pace of adoption of all kinds of home delivery. We have arrived at a tipping point where there is not enough labor for all the fulfillment centers now in existence, even as Amazon and other retailers are striving to achieve deliveries within a couple of hours of receiving an order.

Beneath our placid exteriors we are a seething mass of autocatalysis.

Amazon and others are already relying on robots to fetch and move purchased goods in these fulfillment centers, and even to pack items for shipping. There is an enormous incentive to make these robots more intelligent, more capable, and more pleasant for human workers to be around. These robots could be a catalyst for even more fulfillment centers, and for even better robots. Such capable robots would be used in manufacturing, so they might possibly prompt a return of manufacturing to technologically advanced countries that lost it decades ago to regions with lower-cost labor.

And there may be another big role for automation, too. The last-kilometer component of delivery will require faster, more automated solutions in our cities and suburbs. So we may yet see the transportation infrastructure needed to enable more robotic vehicles in these places. And that, in turn, could pave the way (as it were) for truly large-scale deployment of autonomous passenger vehicles.

It would be a revolution on a grand scale. But no more grand than others triggered by autocatalysis over the past couple of centuries. ■

Illustration by Harry Campbell

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ASAD MADNI
AND THE
LIFE-SAVING SENSOR

His pivot away from defense led to a tiny tuning fork that helped prevent SUV rollovers and plane crashes

BY TEKLA S. PERRY | PHOTOGRAPHY BY PETER ADAMS

In 1992, Asad M. Madni sat at the helm of BEI Sensors and Controls, overseeing a product line that included a variety of sensing and inertial-navigation devices. Its customers were less varied—mainly, the aerospace and defense-electronics industries. And he had a problem.

The Cold War had ended, crashing the U.S. defense industry. And business wasn't going to come back anytime soon. BEI needed to identify and capture new customers—and quickly.

Getting those customers would require abandoning the company's mechanical inertial-sensor systems in favor of a new, unproven quartz technology, miniaturizing the quartz sensors, and turning a manufacturer of tens of thousands of expensive sensors a year into a manufacturer of millions of cheaper ones.

Madni led an all-hands push to make that happen—and succeeded beyond what anyone could have imagined with the GyroChip. This inexpensive inertial-measurement sensor was the first such device to be incorporated into automobiles, enabling electronic stability-control (ESC) systems to detect skidding and operate the brakes to prevent rollover accidents. According to the U.S. National Highway Traffic Safety Administration, in the five-year period spanning 2011 to 2015, with ESCs being built into all new cars, the systems saved 7,000 lives in the United States alone.

The device went on to serve as the heart of stability-control systems in countless commercial and private aircraft and U.S. missile guidance systems, too. It even traveled to Mars as part of the Pathfinder Sojourner rover.

For pioneering the GyroChip, and for other contributions in technology development and research leadership, Madni received the 2022 IEEE Medal of Honor.

Engineering wasn't Madni's first choice of profession. He wanted to be a fine artist—a painter. But his family's economic situation in Mumbai, India (then Bombay) in the 1950s and 1960s steered him to engineering—specifically electronics, thanks to his interest in recent innovations embodied in the pocket-size transistor radio. In 1966 he moved to the United States to study electronics at the RCA Institutes in New York City, a school created in the early 1900s to train wireless operators and technicians.

"I wanted to be an engineer who would invent things," Madni says, "one who would do things that would eventually affect humanity. Because if I couldn't affect humanity, I felt that I would have an unfulfilling career."

After two years completing the electronics technology program at the RCA Institutes, Madni went on to the University of California, Los Angeles (UCLA), receiving a B.S. in electrical engineering in 1969. He continued on to a master's and a Ph.D., using digital signal processing along with frequency-domain reflectometry to analyze telecommunications systems for his dissertation research. While studying, he also worked variously at Pacific States University as an instructor, at Beverly Hills retailer David Orgell in inventory management, and at Pertec as an engineer designing computer peripherals.

Then, in 1975, newly engaged and at the insistence of a former classmate, he applied for a job in Systron Donner's microwave division.

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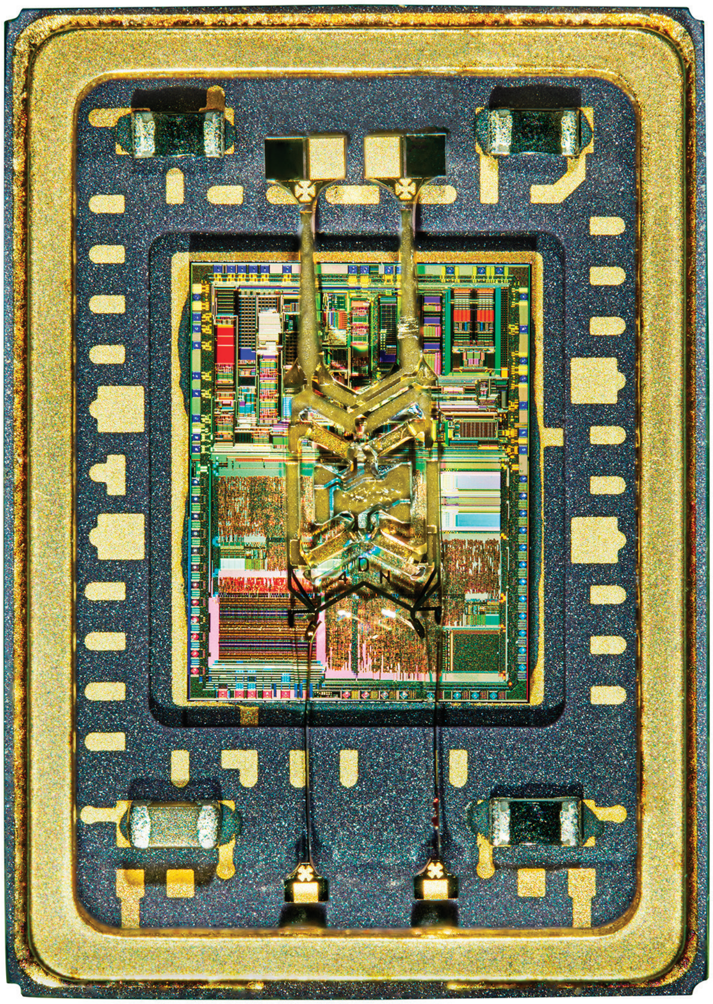
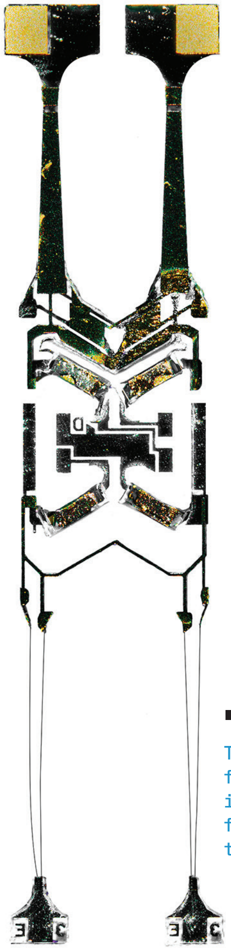


The GyroChip enabled electronic stability-control systems in automobiles to detect skidding and prevented countless rollover accidents.



This quartz tuning fork responds to inertial forces and forms the heart of the GyroChip.

Madni started off at Systron Donner by designing the world's first spectrum analyzer with digital storage. He had never actually used a spectrum analyzer before—these were very expensive instruments at the time—but he knew enough about the theory to talk himself into the job. He then spent six months working in testing, picking up practical experience with the instruments before attempting to redesign one.

The project took two years and, Madni reports, led to three significant patents that started his climb "to bigger and better things." It also taught him, he says, an appreciation for the difference between "what it is to have theoretical knowledge and what it is to commercialize technology that can be helpful to others."

He went on to develop numerous RF and microwave systems and instrumentation for the U.S. military, including an analyzer for communications lines and attached antennas built for the Navy, which became the basis for his doctoral research.

Though he moved quickly into the management ranks, eventually climbing to chairman, president, and CEO of Systron Donner, former colleagues say he never entirely left the lab behind. His technical mark was on every project he became involved in, including the groundbreaking work that led to the GyroChip.

Before we talk about the little quartz sensor that became the heart of the GyroChip, here's a little background on the inertial-measurement units of the 1990s. An IMU measures several properties of an object: its specific force (the acceleration that's not due to gravity); its angular rate of rotation around an axis; and, sometimes, its orientation in three-dimensional space.

In the early 1990s, the typical IMU used mechanical gyroscopes for angular-rate sensing. A package with three highly accurate spinning mass gyroscopes was about the size of a toaster oven and weighed about a kilogram. Versions that used ring-laser gyroscopes or fiber-optic gyroscopes were somewhat smaller, but all high-accuracy optical and mechanical gyros of the time cost thousands of dollars.

So that was the IMU in 1990, when Systron Donner sold its defense-electronics businesses to BEI Technologies, a publicly traded spinoff of BEI Electronics, itself a spinoff of the venerable Baldwin Piano Co. The device was big, heavy, expensive, and held moving mechanical parts that suffered from wear and tear, affecting reliability.

Shortly before the sale, Systron Donner had licensed a patent for a completely different type of rate sensor from a group of U.S. inventors. It was little more than a paper design at the time, Madni says, but the company had started investing some of its R&D budget in implementing the technology.

The design centered on a tiny, dual-ended vibrating tuning fork carved out of quartz using standard silicon-wafer-processing techniques. The tines of the fork would be deflected by the Coriolis effect, the inertial force acting on an object as it resists being pulled from its plane of rotation. Because quartz has piezoelectric properties, changes in forces acting upon it cause changes in electric charge. These changes could be converted into measurements of angular velocity.

The project continued after Systron Donner's divisions became part of BEI, and in the early 1990s BEI was manufacturing some 10,000 quartz gyroscopic sensors annually for a classified defense project. But with the fall of the Soviet Union and ensuing rapid contraction of the U.S. defense industry, Madni worried that there would be no more customers—at least for a long time—for these tiny new sensors or even for the traditional mechanical sensors that were the main part of the division's business.

"We had two options," Madni recalls. "We stick out in the sands and peacefully die, which would be a shame, because nobody else has this technology. Or we find somewhere else we can use it."

The hunt was on. Madni says he and members of his research and marketing teams went to every sensors conference they could find, talking to anyone who used inertial sensors, regardless of whether the applications were industrial, commercial, or space. They showed the quartz angular-rate sensors the company had developed, touting their price, precision, and reliability, and laid out a path in which the devices became smaller and cheaper in just a few years. NASA was interested—and eventually used the devices in the Mars Pathfinder Sojourner rover and the systems that allowed astronauts to move about in space untethered. Boeing and other aircraft and avionics-system manufacturers began adopting the devices.

But the automotive industry clearly represented the biggest potential market. In the late 1980s, car companies had begun introducing basic traction-control systems in their high-end vehicles. These systems monitored steering-wheel position, throttle position, and individual wheel speeds, and could adjust engine speed and braking when they detected a problem, such as one wheel turning faster than another. They couldn't, however, detect when the direction of a car's turn on the road didn't match the turn of the steering wheel, a key indicator of an unstable skid that could turn into a rollover.

“If I couldn’t affect humanity, I felt that I would have an unfulfilling career.”

The industry was aware this was a deficiency, and that rollover accidents were a significant cause of deaths from auto accidents. Automotive-electronics suppliers like Bosch were working to develop small, reliable angular-rate sensors, mostly out of silicon, to improve traction control and rollover prevention, but none were ready for prime time.

Madni thought this was a market BEI could win. In partnership with Continental Teves of Frankfurt, Germany, BEI set out to reduce the size and cost of the quartz devices and manufacture them in quantities unheard of in the defense industry, planning to ramp up to millions annually.

This major pivot—from defense to one of the most competitive mass-market industries—would require big changes for the company and for its engineers. Madni took the leap.

“I told the guys, ‘We are going to have to miniaturize it. We are going to have to bring the price down—from $1,200 to $1,800 per axis to $100, then to $50, and then to $25. We are going to have to sell it in hundreds of thousands of units a month and then a million and more a month.’”

To do all that, he knew that the design for a quartz-based rate sensor couldn’t have one extra component, he says. And that the manufacturing, supply chain, and even sales management had to be changed dramatically.

“I told the engineers that we can’t have anything in there other than what is absolutely needed,” Madni recalls. “And some balked—too used to working on complex designs, they weren’t interested in doing a simple design. I tried to explain to them that what I was asking them to do was more difficult than the complex things they’ve done,” he says. But he still lost some high-level design engineers.

“The board of directors asked me what I was doing, [saying] that those were some of our best people. I told them that it wasn’t a question of the best people; if people are not going to adapt to the current needs, what good do they do?”

Others were willing to adapt, and he sent some of those engineers to visit watch manufacturers in Switzerland to learn about handling quartz; the watch industry had been using the material for decades. And he offered others training by experts in the automotive industry, to learn about its operations and requirements.

The changes needed were not easy, Madni remembers. “We have a lot of scars on our back. We went through a hell of a process. But during my tenure, BEI became the world’s largest supplier of sensors for automotive stability and rollover prevention.”

In the late 1990s, Madni says, the market for electronic stability-control systems exploded, as a result of an incident in 1997. An automotive journalist, testing a new Mercedes on a test track, was performing the so-called *elchtest*, often referred to as the “elk test”: He swerved at normal speed, intending to simulate avoiding a moose crossing the road, and the car rolled over. Mercedes and competitors responded to the bad publicity by embracing stability-control systems, and GyroChip demand skyrocketed.

Thanks to the deal with Continental Teves, BEI held a large piece of the automotive market for many years. BEI wasn’t the only game in town at that point—Germany’s Bosch had begun producing silicon-based MEMS rate sensors in 1998—but the California company was the only manufacturer using quartz sensors, which at the time performed better than silicon. Today, most manufacturers of automotive-grade rate sensors use silicon, for that technology has matured and such sensors are cheaper to produce.

While manufacturing for the auto market ramped up, Madni continued to look for other markets. He found another big one in the aircraft industry.

The Boeing 737 in the early and mid-’90s had been involved in a series of crashes and incidents that stemmed from unexpected rudder movement. Some of the failures were traced to the aircraft’s power control unit, which incorporated yaw-damping technology. While the yaw sensors weren’t specifically implicated, the company did need to redesign its PCUs. Madni and BEI convinced Boeing to use BEI’s quartz sensors in all of its 737s going forward, as well as retrofitting existing aircraft with the devices. Manufacturers of aircraft for private aviation soon embraced the sensor as well. And eventually the defense business came back.

Today, electronic angular-rate sensors are in just about every vehicle—land, air, or sea. And Madni’s effort to miniaturize them and reduce their cost blazed the trail.

By 2005, BEI's portfolio of technologies had made it an attractive target for acquisition. Besides the rate sensors, it had earned acclaim for its development of the unprecedentedly accurate pointing system created for the Hubble Space Telescope. The sensors and control group had expanded into BEI Sensors & Systems Co., of which Madni was CEO and CTO.

"We weren't looking for a buyer; we were progressing extremely well and looking to still grow. But several people wanted to buy us, and one, Schneider Electric, was relentless. They wouldn't give up, and we had to present the deal to the board."

The sale went through in mid-2005 and, after a brief transition period and turning down a leadership position with Schneider Electric, Madni officially retired in 2006.

While Madni says he's been retired since 2006, he actually retired only from industry, crossing over into a busy life in academia. He has served as an honorary professor at six universities, including the Technical University of Crete, the University of Texas at San Antonio, and the University of Waikato, in New Zealand. In 2011, he joined the faculty of UCLA's electrical and computer-engineering department as a distinguished scientist and distinguished adjunct professor and considers that his home institution. He is on campus weekly to meet with his advisees, who are working in sensing, signal processing, AI for sensor design, and ultrawideband high-speed instrumentation. Madni has advised 25 graduate students to date.

One of his former UCLA students, Cejo K. Lonappan, now principal systems engineer at SILC Technologies, says Madni cares a lot about the impact of what his advisees are doing, asking them to write an executive summary of every research project that goes beyond the technology to talk about the bigger picture.

"Many times in academic research, it is easy to get lost in details, in minor things that seem impressive to the person doing the research," Lonappan says. But Madni "cares a lot about the impact of what we are doing beyond the engineering and scientific community—the applications, the new frontiers it opens."

S.K. Ramesh, a professor and former dean of electrical engineering and computer science at California State University, Northridge, has also seen Madni the advisor in action.

"For him," Ramesh says, "it's not just about engineering. It's about engineering the future, showing how to make a difference in people's lives. And he's not discouraged by challenges."

"We had a group of students who wanted to take a headset used in gaming and use it to create a brain-control interface for wheelchair users," Ramesh says. "We spoke to a neurologist, and he laughed at us, said you couldn't do that, to monitor brain waves with a headset and instantaneously transfer that to a motion command. But Prof. Madni looked at it as how do we solve the problem, and even if we can't solve it, along the way we will learn something by trying."

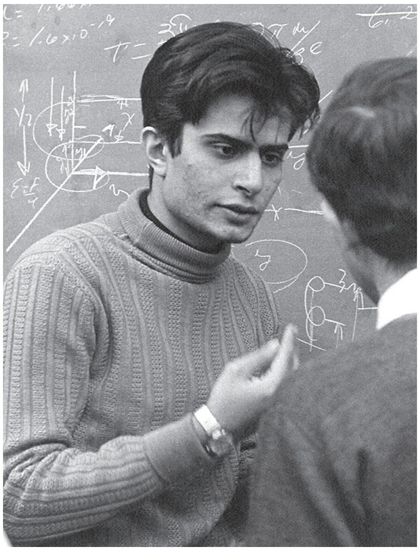
Says Yannis Phillis, a professor at the Technical University of Crete: "This man knows a lot about engineering, but he has a wide range of interests. When we met on Crete for the first time, for example, I danced a solo Zeibekiko; it has roots from ancient Greece. He asked me questions left and right about it, why this, why that. He is curious about society, about human behavior, about the environment—and, broadly speaking, the survival of our civilization."

Madni went into engineering hoping to affect humanity with his work. He is satisfied that, in at least some ways, he has done so.

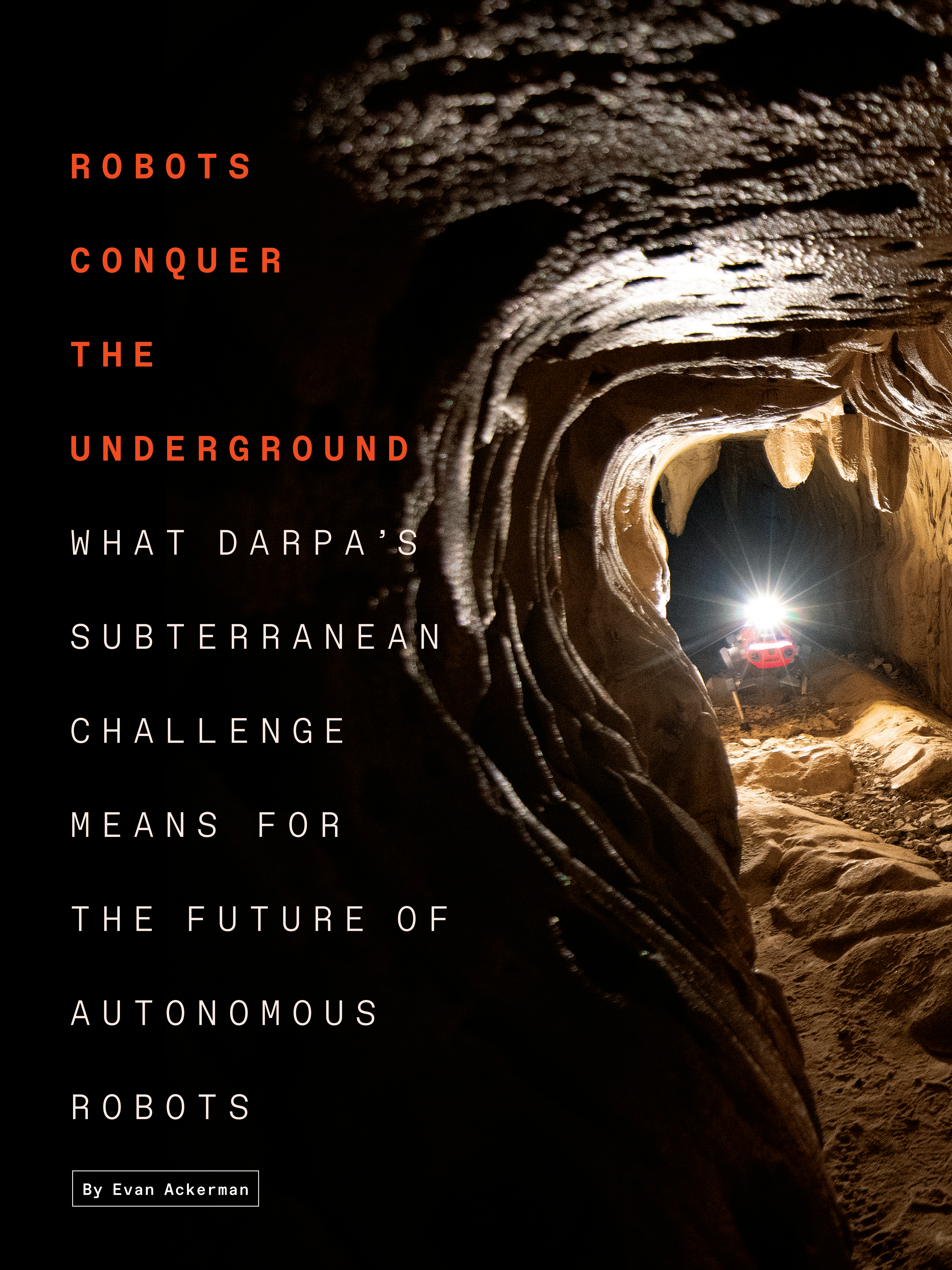
"The space applications have enhanced the understanding of our universe, and I was fortunate to play a part of that," he says. "My contributions [to automotive safety] in their own humble way have been responsible for saving millions of lives around the world. And my technologies have played a role in the defense and security of our nation. It's been the most gratifying career." ■

■ ■ ■

Asad Madni explains a problem in electronic ballistics to a classmate at the RCA Institutes in 1966 [left]. In 1977, Madni [seated, center] discusses the communications-line analyzer he developed for the U.S. Navy.



ASAD MADNI



ROBOTS CONQUER THE UNDERGROUND

WHAT DARPA'S SUBTERRANEAN CHALLENGE MEANS FOR THE FUTURE OF AUTONOMOUS ROBOTS

By Evan Ackerman

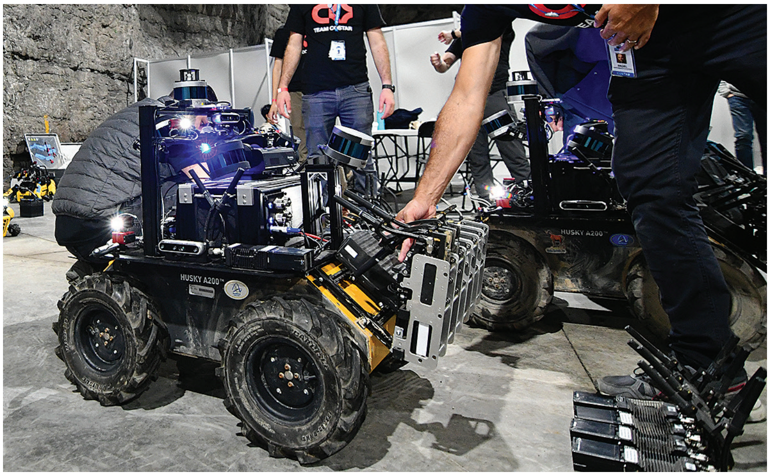
Deep below the Louisville, Ky., zoo lies a network of enormous caverns carved out of limestone. The caverns are dark. They're dusty. They're humid. And during one week in September 2021, they were full of the most sophisticated robots in the world. The robots (along with their human teammates) were there to tackle a massive underground course designed by DARPA, the Defense Advanced Research Projects Agency, as the culmination of its three-year Subterranean Challenge.

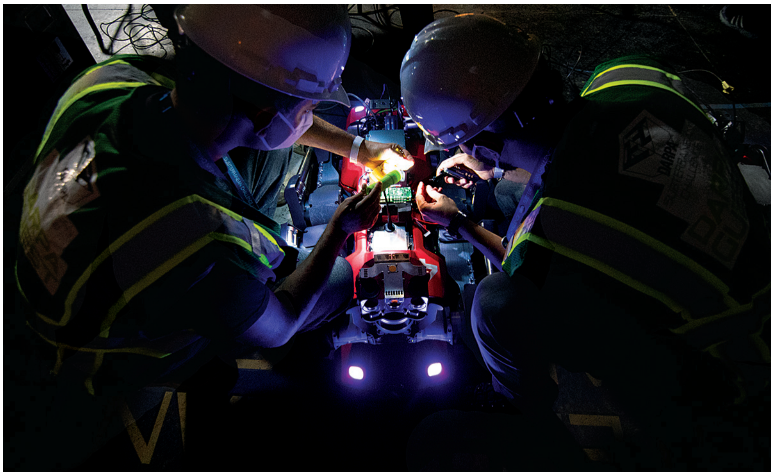
The SubT was first announced in early 2018. DARPA designed the competition to advance practical robotics in extreme conditions, based around three distinct underground environments: human-made tunnels, the urban underground, and natural caves. To do well, the robots would have to work in teams to traverse and map completely unknown areas spanning kilometers, search out a variety of artifacts, and identify their locations with pinpoint accuracy under strict time constraints. To more closely mimic the scenarios in which first responders might utilize autonomous robots, robots experienced darkness, dust, smoke, and even DARPA-controlled rockfalls that occasionally blocked their progress.

With direct funding plus prize money that reached into the millions, DARPA encouraged international collaborations among top academic institutions as well as industry. A series of three preliminary circuit events would give teams experience with each environment.

During the Tunnel Circuit event, which took place in August 2019 in the National

An ANYmal robot from Team Cerberus autonomously explores a cave on DARPA's Subterranean Challenge course.





Team CoSTAR, a collaboration between NASA's JPL, MIT, Caltech, KAIST, and LTU, inspects the communications-node deployment system on their Husky wheeled robots [top]. CoSTAR's pack of quadrupeds, consisting of Spot robots from Boston Dynamics modified with customized autonomy payloads [middle], undergo a hardware check before their final competition run. The Spots are wearing "socks" made from cut-up mountain-bike tires, cable ties, and black tape. Despite the ruggedness of many of the robots, as research platforms, most demanded careful attention from their human teammates, including Team Cerberus [bottom].

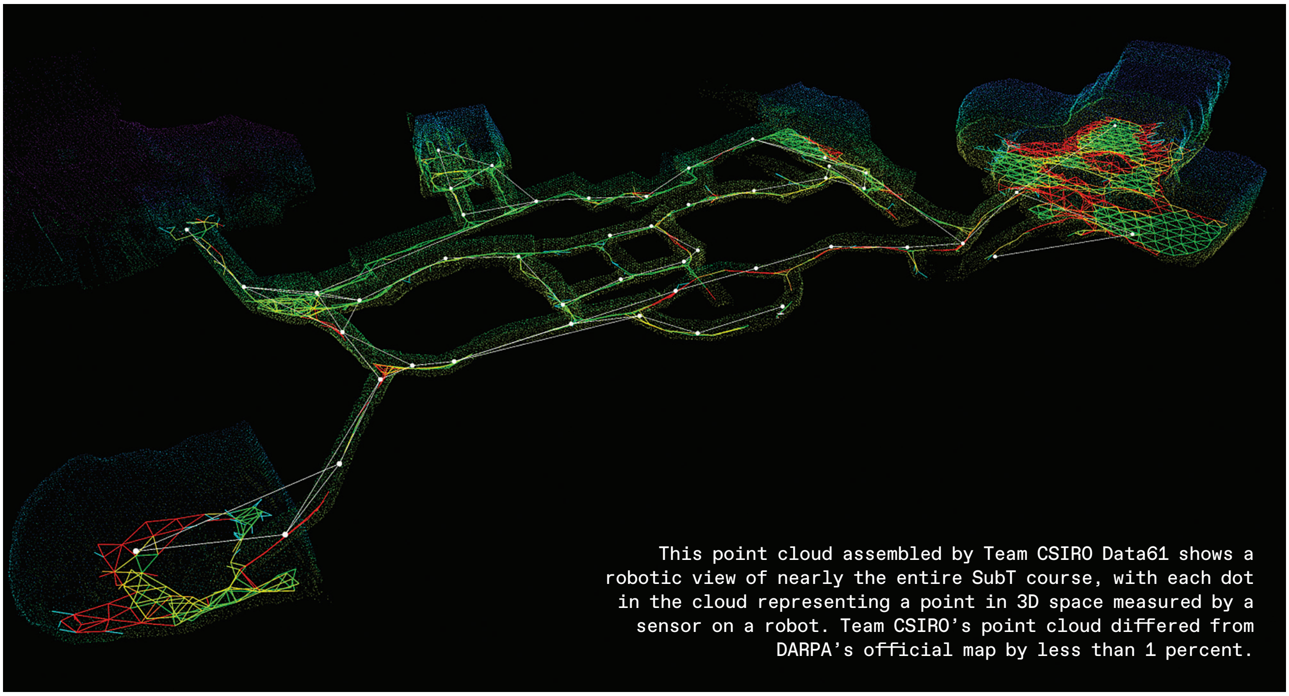
Institute for Occupational Safety and Health's experimental coal mine, on the outskirts of Pittsburgh, many teams lost communication with their robots after the first bend in the tunnel. Six months later, at the Urban Circuit event, held at an unfinished nuclear power station in Satsop, Wash., teams beefed up their communications with everything from a straightforward tethered Ethernet cable to battery-powered mesh network nodes that robots would drop like breadcrumbs as they went along, ideally just before they passed out of communication range. The Cave Circuit, scheduled for the fall of 2020, was canceled due to COVID-19.

By the time teams reached the SubT Final Event in the Louisville Mega Cavern, the focus was on autonomy rather than communications. As in the preliminary events, humans weren't permitted on the course, and only one person from each team was allowed to interact remotely with the team's robots, so direct remote control was impractical. It was clear that teams of robots able to make their own decisions about where to go and how to get there would be the only viable way to traverse the course quickly.

DARPA outdid itself for the final event, constructing an enormous kilometer-long course within the existing caverns. Shipping containers connected end to end formed complex networks, and many of them were carefully sculpted and decorated to resemble mining tunnels and natural caves. Offices, storage rooms, and even a subway station, all built from scratch, comprised the urban segment of the course. Teams had one hour to find as many of the 40 artifacts as possible. To score a point, the robot would have to report the artifact's location back to the base station at the course entrance, which would be a challenge in the far reaches of the course where direct communication was impossible.

Eight teams competed in the SubT Final, and most brought a carefully curated mix of robots designed to work together. Wheeled vehicles offered the most reliable mobility, but quadrupedal robots proved surprisingly capable, especially over tricky terrain. Drones allowed complete exploration of some of the larger caverns.

Photography by Evan Ackerman



This point cloud assembled by Team CSIRO Data61 shows a robotic view of nearly the entire SubT course, with each dot in the cloud representing a point in 3D space measured by a sensor on a robot. Team CSIRO's point cloud differed from DARPA's official map by less than 1 percent.

CSIRO DATA61

By the end of the final competition, two teams had each found 23 artifacts: Team Cerberus—a collaboration of the University of Nevada, Reno; ETH Zurich; the Norwegian University of Science and Technology; the University of California, Berkeley; the Oxford Robotics Institute; Flyability; and the Sierra Nevada Corp.—and Team CSIRO Data61—consisting of CSIRO's Data61; Emesent; and Georgia Tech. The equal scores triggered a tie-breaker rule: Which team had been the quickest to its final artifact? That gave first place to Cerberus, which had been just 46 seconds faster than CSIRO.

Despite coming in second, Team CSIRO's robots achieved the astonishing feat of creating a map of the course that differed from DARPA's ground-truth map by less than 1 percent, effectively matching what a team of expert humans spent many days creating. That's the kind of tangible, fundamental advance SubT was intended to inspire, according to Tim Chung, the DARPA program manager who ran the challenge.

"There's so much that happens underground that we don't often give a lot of thought to, but if you look at the amount of infrastructure that we've built underground, it's just massive," Chung told *IEEE Spectrum*. "There's a lot of opportunity in being able to perceive, understand, and navigate in subterranean environments—there are engineering integration challenges, as well as foundational design challenges and theoretical questions that we have not yet answered. And those are the questions DARPA is most interested in, because that's what's going to change the face of robotics in 5 or 10 or 15 years, if not sooner."

> "THREE YEARS AGO, WE HAD SOME COOL BITS AND PIECES OF TECHNOLOGY, BUT WE DIDN'T HAVE ROBOT SYSTEMS THAT COULD RELIABLY WORK FOR AN HOUR OR MORE WITHOUT A HUMAN HAVING TO GO AND FIX SOMETHING."
>
> —NAVINDA KOTTEGE, TEAM CSIRO DATA61

IEEE Spectrum was in Louisville to cover the Subterranean Final, and we spoke recently with Chung, as well as CSIRO Data61 team lead Navinda Kottege and Cerberus team lead Kostas Alexis about their SubT experience and the influence the event is having on the future of robotics.

TIM CHUNG

DARPA program manager

DARPA has hundreds of programs, but most of them don't involve multiyear international competitions with million-dollar prizes. What was special about the Subterranean Challenge?

T.C.: Every now and then, one of DARPA's concepts warrants a different model for seeking out innovation. It's when you know you have an impending breakthrough in a field, but you don't know exactly how that breakthrough is going to happen, and where the traditional DARPA program model, with a broad announcement followed by proposal selection, might restrict innova-

Illustration by MCKIBILLO

An ANYmal quadruped from Team Cerberus enters the course [top]. During the competition, only robots and DARPA staff were allowed to cross this threshold. The visual markers surrounding the course entrance provided a precise origin point from which the robots would base the maps they created. This allowed DARPA to measure the accuracy of the artifact locations that teams reported to score points. Cerberus's ANYmal exits the urban section of the course, modeled after a subway station [bottom], and enters the tunnel section of the course, based on an abandoned mine.

tion. DARPA saw the SubT Challenge as a way of attracting the robotics community to solving problems that we anticipate being impactful, like resiliency, autonomy, and sensing in austere environments. And one place where you can find those technical challenges coming together is underground.

The skill that these teams had at autonomously mapping their environments was impressive. Can you talk about that?

T.C.: We brought in a team of experts with professional survey equipment who spent many days making a precisely calibrated ground-truth map of the SubT course. And then during the competition, we saw these robots delivering nearly complete coverage of the course in under an hour—I couldn't believe how beautiful those point clouds were! [See the point cloud image on p. 33.] I think that's really an accelerant. When you can trust your map, you have so much more actionable situational awareness. It's not a solved problem, but when you can attain the level of fidelity that we've seen in SubT, that's a gateway technology with the potential to unlock all sorts of future innovation.

Autonomy was a necessary part of SubT, but having a human in the loop was critical as well. Do you think that humans will continue to be a necessary part of effective robotic teams, or is full autonomy the future?

T.C.: Early in the competition, we saw a lot of hand-holding, with humans giving robots low-level commands. But teams quickly realized that they needed a more autonomous approach. Full autonomy is hard, though, and I think humans will continue to play a pretty big role, just a role that needs to evolve and change into something that focuses on what humans do best.

I think that progressing from human operators to human supervisors will enhance the types of missions that human-robot teams will be able to conduct. In the final event, we saw robots on the course exploring and finding artifacts, while the human supervisor was focused on other stuff and not even paying attention to the robots. That was so cool. The robots were doing what they needed to do, leaving the human free to make high-level decisions. That's a big change: from what was basically remote teleoperation to "you robots go off and do your thing and I'll do mine." And it's incumbent on the robots to become even more capable so that the transition [of the human] from operator to supervisor can occur.

What are some remaining challenges for robots in underground environments?

T.C.: Traversability analysis and reasoning about the environment are still a problem. Robots will be able to move through these environments at a faster clip if they can understand a little bit

Photography by Evan Ackerman

more about where they're stepping or what they're flying around. So, despite the fact that they were one to two orders of magnitude faster than humans for mapping purposes, the robots are still relatively slow. Shaving off another order of magnitude would really help change the game. Speed would be the ultimate enabler and have a dramatic impact on first-response scenarios, where every minute counts.

What difference do you think SubT has made, or will make, to robotics?
T.C.: The fact that many of the technologies being used in the SubT Challenge are now being productized and commercialized means that the time horizon for robots to make it into the hands of first responders has been far shortened, in my opinion. It's already happened, and was happening, even during the competition itself, and that's a really great impact.

NAVINDA KOTTEGE

CSIRO
Data61
team lead

What's difficult and important about operating robots underground?
N.K.: The fact that we were in a subterranean environment was one aspect of the challenge, and a very important aspect, but if you break it down, what the SubT Challenge meant was that we were in a GPS-denied environment, where you can't rely on communications, with very difficult mobility challenges. There are many other scenarios where you might encounter these things—the Fukushima nuclear disaster, for example, wasn't underground, but communication was a massive issue for the robots they tried to send in. The Amazon rainforest is another example where you'd encounter similar difficulties in communication and mobility. So we saw how each of these component technologies that we would have to develop and mature would have applications in many other domains beyond the subterranean.

The subway station platform [top] incorporated many challenges for robots. Wheeled and tracked robots had particular difficulty with the rails. DARPA hid artifacts in the ceiling of the subway station (accessible only by drone), as well as under a grate in the platform floor. In addition to building many customized tunnels and structures inside the Louisville Mega Cavern, DARPA also incorporated the cavern itself into the course. This massive room [bottom] rewarded robots that managed to explore it with several additional artifacts.

Where is the right place for a human in a human-robot team?
N.K.: There are two extremes. One is that you push a button and the robots go and do their thing. The other is what we call "human in the loop," where it's essentially remote control through high-level commands. But if the human is taken out of the loop, the loop breaks and the system stops, and we were experiencing that with brittle communications. The middle ground is a "human on the loop" concept, where you have a human supervisor who sets mission-level goals, but if the human is taken off of the loop, the loop can still run. The human added

Illustration by MCKIBILLO

value because they had a better overview of what was happening across the whole scenario, and that's the sort of thing that humans are super, super good at.

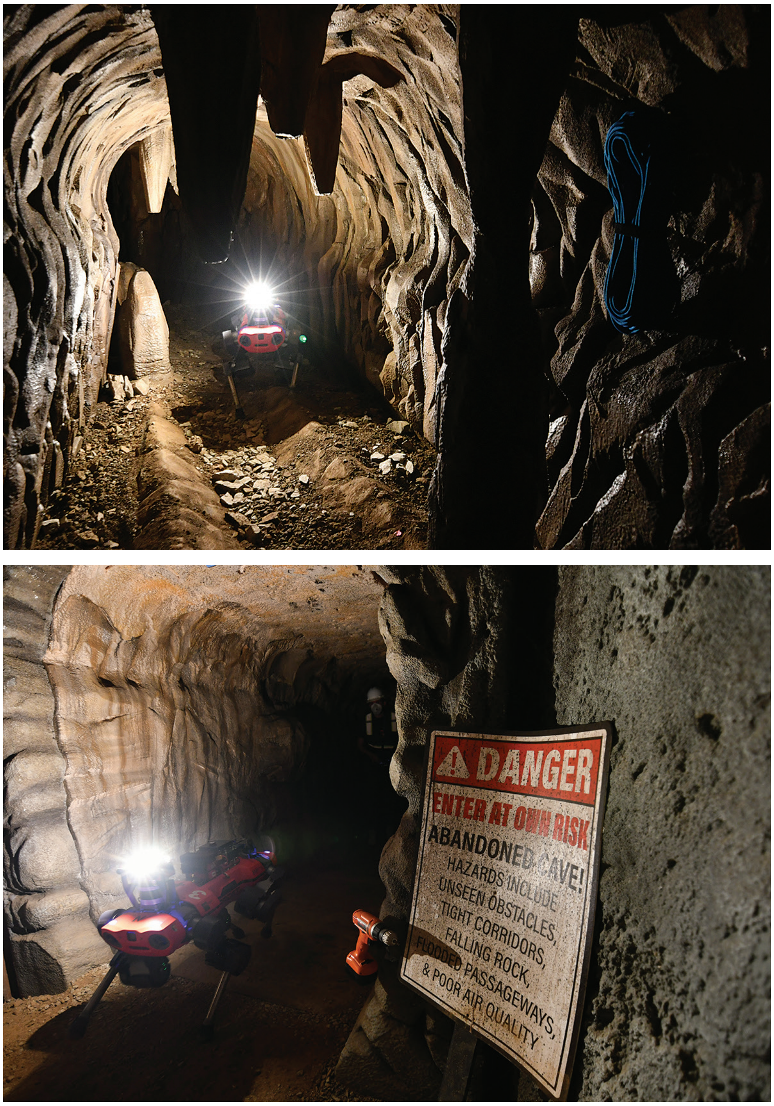
How did SubT advance the field of robotics?

N.K.: For field robots to succeed, you need multiple things to work together. And I think that's what was forced upon us by the level of complexity of the SubT Challenge. This whole notion of being able to reliably deploy robots in real-world scenarios was, to me, the key thing. Looking back at our team, three years ago we had some cool bits and pieces of technology, but we didn't have robot systems that could reliably work for an hour or more without a human having to go and fix something. That was one of the biggest advances we had, because now, as we continue this work, we don't even have to think twice about deploying our robots and whether they'll destroy themselves if we leave them alone for 10 minutes. It's that level of maturity that we've achieved, thanks to the robustness and reliability that we had to engineer into our systems to be successful at SubT, and now we can start focusing on the next step: What can you do when you have a fleet of autonomous robots that you can rely on?

Your team of robots created a map of the course that differed from DARPA's official map by less than 1 percent. That's amazing.

N.K.: I got contacted immediately after the final event by the company that DARPA brought in to do the ground-truth mapping of the SubT course. They'd spent 100 person-hours using very expensive equipment to make their map, and they wanted to know how in the world we got our map in under an hour with a bunch of robots. It's a good question! But the context is that our one hour of mapping took us 15 years of development to get to that stage.

There's a difference in what's theoretically possible and what actually works in the real world. In its early stages, our software worked, in that it hit all of the theoretical milestones it was supposed to. But then we started taking it out to the real world and testing it in very difficult environments, and that's where we started finding all the edge cases of where it breaks. Essentially, for the last 10-plus years, we were trying to break our mapping system as much as possible, and that turned it into a really well-engineered solution. Honestly, whenever we see the results of our mapping system, it still surprises us!



Tight cave sections [top] required careful navigation by ground robots. Stalactites and stalagmites were especially treacherous for drones in flight. At the right of the picture, partially hidden by a column, is a blue coil of rope, one of the artifacts. A Team Cerberus ANYmal [bottom] walks past a decorative (but not inaccurate) warning sign, next to a drill artifact.

KOSTAS ALEXIS

Cerberus team lead

What made you decide to participate in the SubT Challenge?

K. A.: What motivated everyone was the understanding that for autonomous robots, this challenge was extremely difficult and relevant. We knew that robotic systems could operate in these environments if humans accompanied them or teleoperated them, but we also knew that

Photography by Evan Ackerman

we were very far away from enabling autonomy. And we understood the value of being able to send robots instead of humans into danger. It was this combination of societal impact and technical challenge that was appealing to us, especially in the context of a competition where you can't just do work in the lab, write a paper, and call it a day—you had to develop something that would work all the way through the finals.

What was the most challenging part of SubT for your team?

K.A.: We are at the stage where we can navigate robots in normal officelike environments, but SubT had many challenges. First, relying on communications with our robots was not possible. Second, the terrain was not easy. Typically, even terrain that is hard for robots is easy for humans, but the natural cave terrain has been the only time I've felt like the terrain was a challenge for humans too. And third, there's the scale of kilometer-size environments. The robots had to demonstrate a level of robustness and resourcefulness in their autonomy and functionality that the current state of the art in robotics could not demonstrate. The great thing about the SubT Challenge was that DARPA started it knowing that robotics did not have that capacity but asked us to deliver a competitive team of robots three years down the road. And I think that approach went well for all the teams. It was a great push that accelerated research.

As robots get more autonomous, where will humans fit in?

K.A.: It is a fact now that we can have very good maps from robots, and it is a fact that we have object detection, and so on. However, we do not have a way of correlating all the objects in the environment and their possible interactions. So, although we can create awesome, beautiful, accurate maps, we are not equally good at reasoning.

While most of the course was designed to look as much like real underground environments as possible, DARPA also included sections that posed very robot-specific challenges. Robots had the potential to get disoriented in this blank white hallway (part of the urban section of the course) if they couldn't identify unique features to differentiate one part of the hallway from another.

This is really about time. If we were performing a mission where we wanted to guarantee full exploration and coverage of a place with no time limit, we likely wouldn't need a human in the loop—we can automate this fully. But when time is a factor and you want to explore as much as you can, then the human ability to reason through data is very valuable. And even if we can make robots that sometimes perform as well as humans, that doesn't necessarily translate to novel environments.

The other aspect is societal. We make robots to serve us, and in all of these critical operations, as a roboticist myself, I would like to know that there is a human making the final calls.

Do you think SubT was able to solve any significant challenges in robotics?

K.A.: One thing, of which I'm very proud for my team, is that SubT established that legged robotic systems can be deployed under the most arbitrary of conditions. [Team Cerberus deployed four ANYmal C quadrupedal robots from Swiss robotics company ANYbotics in the final competition.] We knew before SubT that legged robots were magnificent in the research domain, but now we also know that if you have to deal with complex environments on the ground or underground, you can take legged robots combined with drones and you should be good to go.

When will we see practical applications of some of the developments made through SubT?

K.A.: I think commercialization will happen much faster through SubT than what we would normally expect from a research activity. My opinion is that the time scale is counted in terms of months—it might be a year or so, but it's not a matter of multiple years, and typically I'm conservative on that front.

In terms of disaster response, now we're talking about responsibility. We're talking about systems with virtually 100 percent reliability. This is much more involved, because you need to be able to demonstrate, certify, and guarantee that your system works across so many diverse use cases. And the key question: Can you trust it? This will take a lot of time. With SubT, DARPA created a broad vision. I believe we will find our way toward that vision, but before disaster response, we will first see these robots in industry. ■

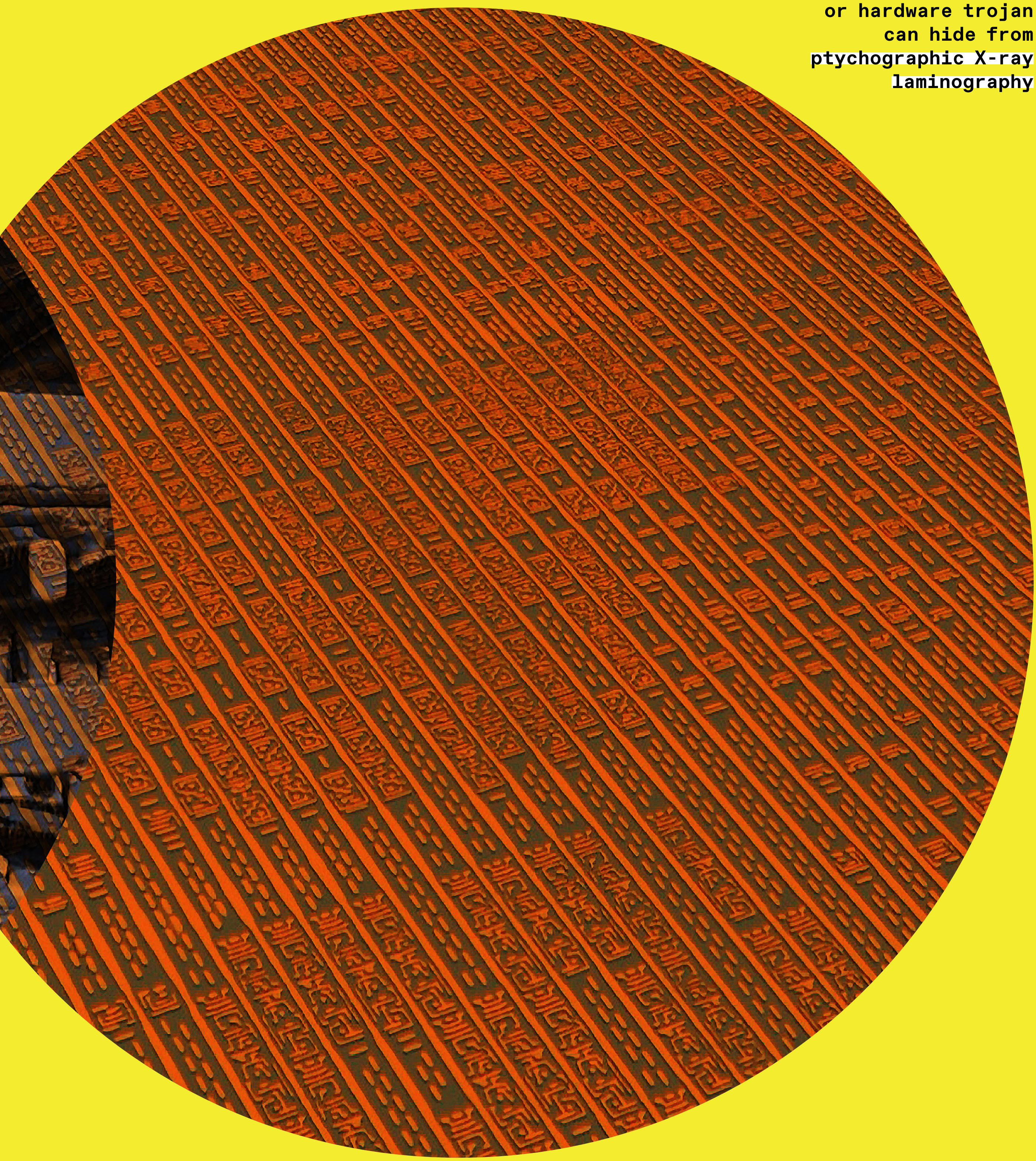
> "THAT'S A BIG CHANGE: FROM WHAT WAS BASICALLY REMOTE TELEOPERATION TO 'YOU ROBOTS GO OFF AND DO YOUR THING AND I'LL DO MINE.'"
>
> —TIM CHUNG, DARPA

Illustration by MCKIBILLO

THE NAKED CHIP

BY ANTHONY F.J. LEVI
& GABRIEL AEPPLI

No trade secret or hardware trojan can hide from ptychographic X-ray laminography



X-ray–based techniques can reconstruct the interconnects in a chip layer by layer [above] and in 3D [left] without destroying it.

WHEN YOU'RE BAKING A CAKE, it's hard to know when the inside is in the state you want it to be. The same is true—with much higher stakes—for microelectronic chips: How can engineers confirm that what's inside has truly met the intent of the designers? How can a semiconductor design company tell whether its intellectual property was stolen? Much more worrisome, how can anyone be sure a kill switch or some other hardware trojan hasn't been secretly inserted?

Today, that probing is done by grinding away each of the chip's many layers and inspecting them using an electron microscope. It's slow going and, of course, destructive, making this approach hardly satisfactory for anybody.

One of us (Levi) works with semiconductors and the other (Aeppli) with X-rays. So, after pondering this problem, we considered using X-rays to nondestructively image chips. You'd need to go beyond the resolution used in medical X-ray scanners. But it was clear to us that the needed resolution was possible. At that moment, what we've been calling the "chip scan" project was born.

Several years later, we've made it possible to map the entire interconnect structure of even the most advanced and complex processors without destroying them. Right now, that process takes more than a day, but improvements over the next few years should enable the mapping of entire chips within hours.

This technique—called pychographic X-ray laminography—requires access to some of the world's most powerful X-ray light sources. But most of these facilities are, conveniently, located close to where much of the advanced chip design happens. So as access to this technique expands, no flaw, failure, or fiendish trick will be able to hide.

AFTER DECIDING TO PURSUE this approach, our first order of business was to establish what state-of-the-art X-ray techniques could do. That was done at the Paul Scherrer Institute (PSI) in Switzerland, where one of us (Aeppli) works. PSI is home to the Swiss Light Source (SLS) synchrotron, one of the 15 brightest sources of coherent X-rays built so far.

Coherent X-rays differ from what's used in a medical or dental office in the same way that the highly collimated beam of light from a laser pointer differs from light emitted in all directions from an incandescent bulb. The SLS and similar facilities generate highly coherent beams of X-ray photons by first accelerating electrons almost to the speed of light. Then, magnetic fields deflect those electrons, inducing the production of the desired X-rays.

To see what we could do with the SLS, our multidisciplinary team bought an Intel Pentium G3260 processor from a local store for about US $50 and removed the packaging to expose the silicon. (This CPU was manufactured using 22-nanometer CMOS FinFET technology.)

Like all such chips, the G3260's transistors are made of silicon, but it's the arrangement of metal interconnects that link them up to form circuits. In a modern processor, interconnects are built in more than 15 layers, which from above look like a map of a city's street grid. The lower layers, closer to the silicon, have incredibly fine features, spaced just nanometers apart in today's most advanced chips. As you ascend the interconnect layers, the features become sparser and bigger, until you reach the top, where electrical contact pads connect the chip to its package.

We began our examination by cutting out a 10-micrometer-wide cylinder from the G3260. We had to take this destructive step because it greatly simplified things. Ten micrometers is less than half

Our first technique, ptychographic X-ray computed tomography, was tested first on a portion of a 22-nanometer Intel processor constructing a detailed 3D image of the chip's interconnects.

PREVIOUS PAGES AND THIS PAGE: SLS-USC CHIP-SCAN TEAM

the penetration depth of the SLS's photons, so with something this small we'd be able to detect enough photons passing through the pillar to determine what was inside.

We placed the sample on a mechanical stage to rotate it about its cylindrical axis and then fired a coherent beam of X-rays through the side. As the sample rotated, we illuminated it with a pattern of overlapping 2-µm-wide spots.

At each illuminated spot, the coherent X-rays diffracted as they passed through the chip's tortuous tower of copper interconnects, projecting a pattern onto a detector, which was stored for subsequent processing. The recorded projections contained enough information about the material through which the X-rays traveled to determine the structure in three dimensions. This approach is called ptychographic X-ray computed tomography (PXCT). Ptychography is the computational process of producing an image of something from the interference pattern of light through it.

THE UNDERLYING PRINCIPLE behind PXCT is relatively simple, resembling the diffraction of light through slits. You might recall from your introductory physics class that if you shine a coherent beam of light through a slit onto a distant plane, the experiment produces what's called a Fraunhofer diffraction pattern. This is a pattern of light and dark bands, or fringes, spaced proportionally to the ratio of the light's wavelength divided by the width of the slit.

If, instead of shining light through a slit, you shine it on a pair of closely spaced objects, ones so small that they are effectively points, you will get a different pattern. It doesn't matter where in the beam the objects are. As long as they stay the same distance from each other, you can move them around and you'd get the same pattern.

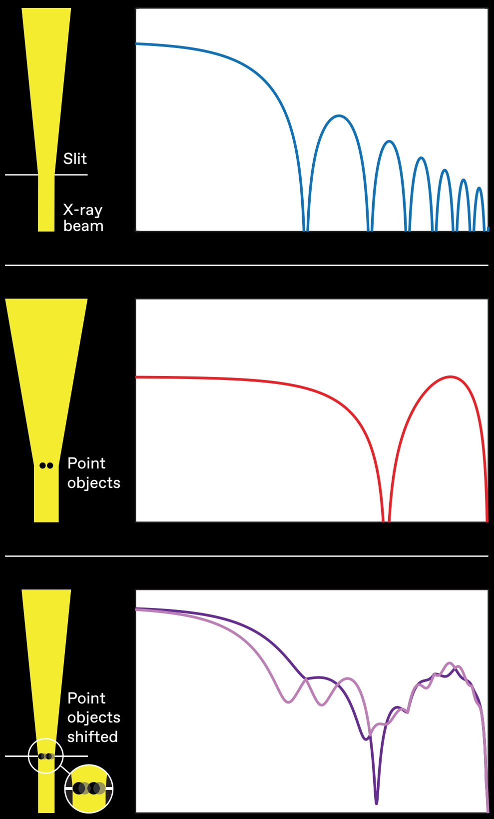
By themselves, neither of these phenomena will let you reconstruct the tangle of interconnects in a microchip. But if you combine them, you'll start to see how it could work. Put the pair of objects within the slit. The resulting interference pattern is derived from the diffraction due to a combination of slit and object, revealing information about the width of the slit, the distance between the objects, and the relative position of the objects and the slit. If you move the two points slightly, the interference pattern shifts. And it's that shift that allows you to calculate exactly where the objects are within the slit.

Any real sample can be treated as a set of pointlike objects, which give rise to complex X-ray scattering patterns. Such patterns can be used to infer how those pointlike objects are arranged in two dimensions. And the principle can be used to map things out in three dimensions by rotating the sample within the beam, a process called tomographic reconstruction.

You need to make sure you're set up to collect enough data to map the structure at the required resolution. Resolution is determined by the X-ray wavelength, the size of the detector, and a few other parameters. For our initial measurements with the SLS, which used 0.21-nm-wavelength X-rays, the detector had to be placed about 7 meters from the sample to reach our target resolution of 13 nm.

In March 2017, we demonstrated the use of PXCT for nondestructive imaging of integrated circuits by publishing some very pretty 3D images of copper interconnects in the Intel Pentium G3260 processor. Those images reveal the three-dimensional character and complexity of electrical interconnects in this CMOS integrated circuit. But they also captured interesting details such as the imperfections in the metal connections between the layers and the roughness between the copper and the silica dielectric around it.

From this proof-of-principle demonstration alone, it was



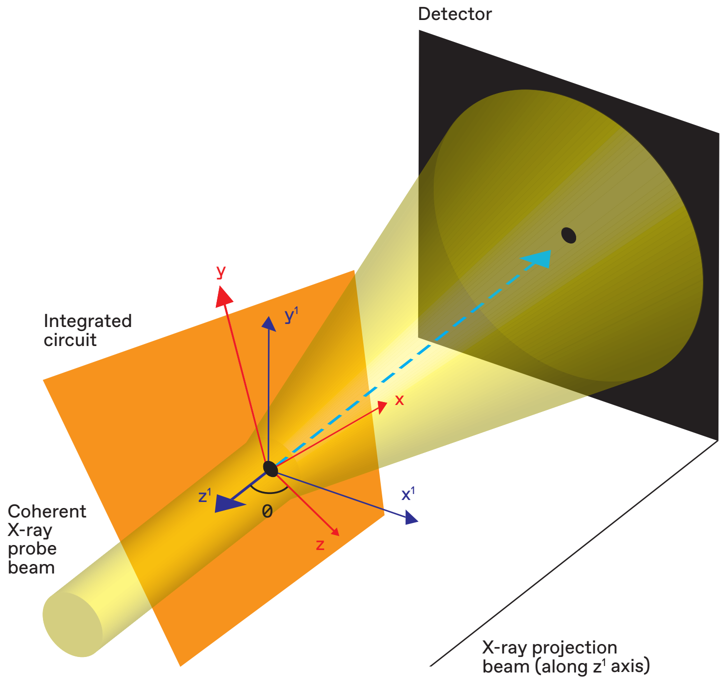
INTERFERENCE BASICS

Some fairly simple X-ray diffraction effects reveal enough information to derive nanoscale structures. Shining X-rays through a small slit [top left] projects the classic Fraunhofer pattern onto a detector [blue, top]. Replace the slit with two pointlike objects [center left], spaced closer together than the slit, and a different pattern is projected [red, center]. Placing the point objects within the slit combines the two interference patterns [dark purple, bottom]. Shifting the objects within the slit [bottom left] alters the relative phase of the interference patterns to produce a new combination [light purple]. Several such interference patterns together reveal the position of objects in an X-ray beam's path.

clear that the technique had potential in failure analysis, design validation, and quality control. So we used PXCT to probe similarly sized cylinders cut from chips built with other companies' technologies. The details in the resulting 3D reconstructions were like fingerprints that were unique to the ICs and also revealed much about the manufacturing processes used to fabricate the chips.

WE WERE ENCOURAGED BY our early success. But we knew we could do better, by building a new type of X-ray microscope and coming up with more effective ways to improve image reconstruction using chip design and manufacturing information. We called the new technique PyXL, shorthand for ptychographic X-ray laminography.

The first thing to deal with was how to scan a whole 10-millimeter-wide chip when we had an X-ray penetration depth of only around 30 µm. We solved this problem by first tilting the chip at an angle relative to the beam. Next, we rotated the sample about the axis perpendicular to the plane of the chip. At the same time we also moved it sideways, raster fashion. This allowed us to scan all parts of the chip with the beam.



PTYCHOGRAPHIC LAMINOGRAPHY

In an edge-on position, this chip [orange] is too thick for X-rays to penetrate. But tilting the chip at an angle [see theta, center] makes the cross section thin enough. The mechanical stage the chip sits on [not shown] then rotates the sample within the X-ray beam around the z axis to project interference patterns onto a detector that can be used to reconstruct the chip's interconnects.

At each moment in this process, the X-rays passing through the chip are scattered by the materials inside the IC, creating a diffraction pattern. As with PXCT, diffraction patterns from overlapping illumination spots contain redundant information about what the X-rays have passed through. Imaging algorithms then infer a structure that is the most consistent with all measured diffraction patterns. From these we can reconstruct the interior of the whole chip in 3D.

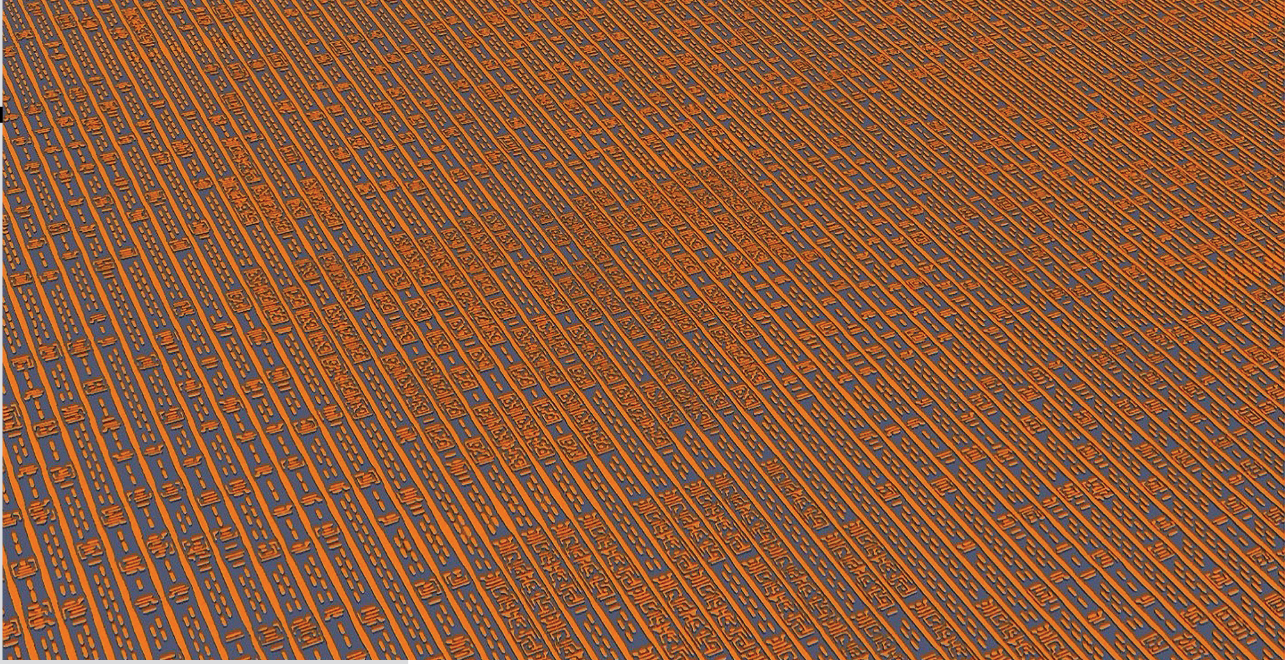
Needless to say, there is plenty to worry about when developing a new kind of microscope. It must have a stable mechanical design, including precise motion stages and position measurement. And it must record in detail how the beam illuminates each spot on the chip and the ensuing diffraction patterns. Finding practical solutions to these and other issues required the efforts of a team of 14 engineers and physicists. The geometry of PyXL also required developing new algorithms to interpret the data collected. It was hard work, but by late 2018 we had successfully probed 16-nm ICs, publishing the results in October 2019.

In these experiments, we were able to use PyXL to peel away each layer of interconnects virtually to reveal the circuits they form. As an early test, we inserted a small flaw into the design file for the interconnect layer closest to the silicon. When we compared this version of the layer with the PyXL reconstruction of the chip, the flaw was immediately obvious.

IN PRINCIPLE, a few days of work is all we'd need to use PyXL to obtain meaningful information about the integrity of an IC manufactured in even the most advanced facilities. Today's cutting-edge processors can have interconnects just tens of nanometers apart, and our technique can, at least in principle, produce images of structures smaller than 2 nm.

But increased resolution does take longer. Although the hardware we've built has the capacity to completely scan an area up to 1.2 by 1.2 centimeters at the highest resolution, doing so would be impractical. Zooming in on an area of interest would be a better use of time. In our initial experiments, a low-resolution (500-nm) scan over a square portion of a chip that was 0.3 mm on a side took 30 hours to acquire. A high-resolution (19-nm) scan of a much smaller portion of the chip, just 40 µm wide, took 60 hours.

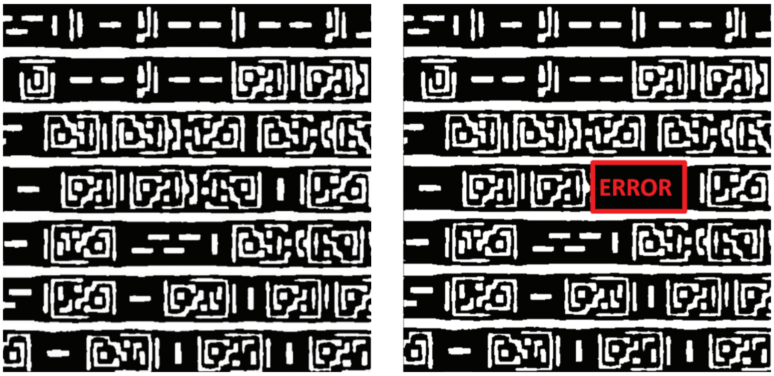
The imaging rate is fundamentally limited by the X-ray flux available to us at SLS. But other facilities boast higher X-ray fluxes, and methods are in the



works to boost X-ray source “brilliance”—a combination of the number of photons produced, the beam’s area, and how quickly it spreads. For example, the MAX IV Laboratory in Lund, Sweden, pioneered a way to boost its brilliance by two orders of magnitude. A further one or two orders of magnitude can be obtained by means of new X-ray optics. Combining these improvements should one day increase total flux by a factor of 10,000.

With this higher flux, we should be able to achieve a resolution of 2 nm in less time than it now takes to obtain 19-nm resolution. Our system could also survey a one-square-centimeter integrated circuit—about the size of an Apple M1 processor—at 250-nm resolution in fewer than 30 hours.

And there are other ways of boosting imaging speed and resolution, such as better stabilizing the probe beam and improving our algorithms to account for the design rules of ICs and the deformation that can result from too much X-ray exposure.



The new version of our X-ray technique, called ptychographic X-ray laminography, can uncover the interconnect structure of entire chips without damaging them, even down to the smallest structures [top]. Using that technique, we could easily discover a (deliberate) discrepancy between the design file and what was manufactured [bottom].

ALTHOUGH WE CAN ALREADY TELL a lot about an IC from just the layout of its interconnects, with further improvements we should be able to discover *everything* about it, including the materials it’s made of. For the 16-nm-technology node, that includes copper, aluminum, tungsten, and compounds called silicides. We might even be able to make local measurements of strain in the silicon lattice, which arises from the multilayer manufacturing processes needed to make cutting-edge devices.

Identifying materials could become particularly important, now that copper-interconnect technology is approaching its limits. In contemporary CMOS circuits, copper interconnects are susceptible to electromigration, where current can kick copper atoms out of alignment and cause voids in the structure. To counter this, the interconnects are sheathed in a barrier material. But these sheaths can be so thick that they leave little room for the copper, making the interconnects too resistive. So alternative materials, such as cobalt and ruthenium, are being explored. Because the interconnects in question are so fine, we’ll need to reach sub-10-nm resolution to distinguish them.

There’s reason to think we’ll get there. Applying PXCT and PyXL to the “connectome” of both hardware and wetware (brains) is one of the key arguments researchers around the world have made to support the construction of new and upgraded X-ray sources. In the meantime, work continues in our laboratories in California and Switzerland to develop better hardware and software. So someday soon, if you’re suspicious of your new CPU or curious about a competitor’s, you could make a fly-through tour through its inner workings to make sure everything is really in its proper place. ■

SLS-USC CHIP-SCAN TEAM

Tesla Inside

THE LAND ROVER DEFENDER GETS AN ELECTRIC MAKEOVER

BY LAWRENCE ULRICH

This vintage Land Rover Defender has been refitted with an electric power train, one originally designed for a Tesla.

E.C.D. AUTOMOTIVE DESIGN

From the outside, this Land Rover Defender looks like any other example of the postwar British classic that conquered the African outback—and the automotive world's heart. But when I step on the accelerator, my own heart jumps. The Defender charges like a lioness on a wildebeest's scent, slaying 60 miles per hour (almost 100 kilometers per hour) in about 5 seconds. That acceleration is so out of character for this doughty old truck, and so fun, that I'm forced to do it again.

Clearly, that's no lazy Rover diesel chugging below the hood—or even a Chevrolet V-8, a current go-to engine for vintage-car fans seeking a contemporary edge. This Defender, known for raiding tombs, has raided Tesla's temple of tech.

The Insta-worthy specimen I'm driving—dubbed "Project Britton" and built by E.C.D. Automotive Design (formerly East Coast Defenders), in Kissimmee, Fla.—highlights the small-but-growing phenomenon of people converting fossil-fueled cars to run on electricity. It's also a plug-in twist on the hottest thing in car customization: "restomods," which update classics with modern power trains, suspensions, and creature comforts, all hidden under their vintage skins.

Around the world, specialists like E.C.D. and its power-train designer and supplier, Electric Classic Cars, in Newton, Wales, will replace a car's petroleum-clogged heart and give it a new, electric lease on life.

For this baby-blue Rover, the conversion includes a powerful electric drive unit from a Tesla Model S P100D, which provides 450 horsepower (331 kilowatts) in this application. That's three times the output of the Buick-based Rover V-8 that first pow-

E.C.D. AUTOMOTIVE DESIGN

ered these trucks in 1979, and nine times that of the anemic 50-hp gasoline engine the Rover boasted at its birth, in 1948.

The car holds about 100 kilowatt-hours' worth of lithium-iron phosphate (LFP) batteries—a lower-cost approach used for the Teslas sold in China and Europe (and recently adopted for standard-range Teslas in the United States).

About 60 percent of those cells go into the front engine bay; the rest reside below the cargo hold. That gives the hardy Rover a range of up to 350 kilometers (about 220 miles)—plenty for weekend joy rides. A port mounted on a rear fender connects a standard CCS (Combined Charging System) plug to an onboard 7-kW charger.

E.C.D. Automotive Design is the brainchild of three British petrolheads, Scott Wallace and brothers Tom and Elliot Humble, who grew up not far from the Lode Lane factory that built the Defender. The company was founded in 2013, after a brainstorming session over a case of beer in a Florida garage.

"We said, 'Let's take a British farm vehicle and turn it into a luxury SUV for the American market,' " Wallace recounts during my tour of E.C.D.'s "Rover Dome," its 45,000-square-foot (about 4,200-square-meter) production facility. "After every beer, it sounded like a better idea."

The lads might want to pop another cold one: Business is rocking, as evidenced by a visit to the company's sparkling 100,000-square-foot (about 9,300-square-meter) production center, set to open in August. There, more than 60 employees and two production lines will have the capacity for 100 conversions a year.

Wallace figures one in five customers will choose an electric power train, with the rest opting for more-traditional, hot-rod-style upgrades such as "LS swaps," named after the LS family of Chevrolet V-8 gasoline engines. EV conversions here and elsewhere are seizing both imaginations and wallets, as classic-car fans focus on improved performance, reliability, and ease of maintenance, with the environmental benefits a green icing on the cake.

Porsches, Jaguars, Fiats, VW Beetles and Buses, even Ferraris, have all gone under the knife, with an increasing number of entrepreneurs serving this growing market. Some major automakers are even getting in on the act. They see a potential sideline in electric versions of the "crate motors" that they've sold for decades to hobbyists, hot-rodders, restorers, and racing teams.

The Land Rover Defender is a good candidate for conversion because it has long had a fanatical following, with 2 million units sold around the globe between 1948 and its retirement in 2016. Rover estimates that 70 percent of these hardy survivors—beginning with the Land Rover "Series" models, with the "Defender" name added in 1990—remain on the road.

Despite some cosmetic changes and steadily upgraded power trains, the design of its stout-yet-primitive chassis barely changed for more than half a century. In America, Defenders have typically been weekend playthings for boomers with fond memories of *Born Free* or "Daktari"—a typical SUV buyer might run screaming after five minutes in this crude, jouncy beast. Roughly 7,000 Americans got their hands on a new Defender via the NAS models that Rover sold to Yanks between 1993 and 1995, with a final encore in 1997.

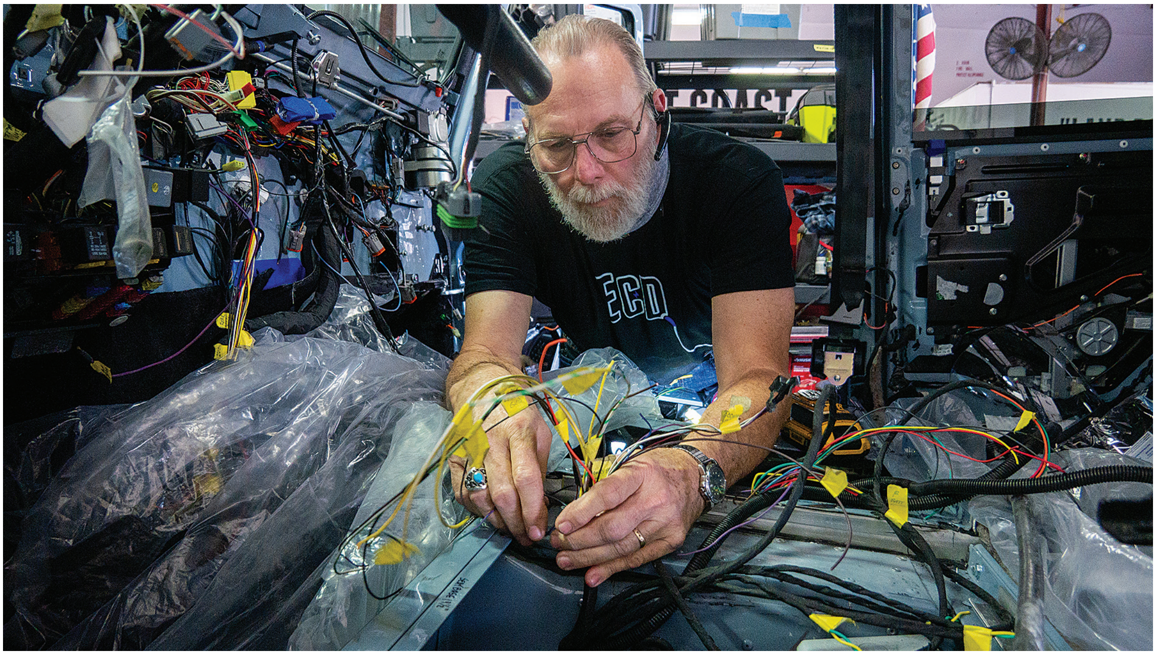
Their rarity only fueled a desire for Defenders among U.S. car buyers, spawning a gray market for imports. Non-NAS Rovers were never officially "federalized" to meet U.S. regulatory standards, so that booming trade led to many confiscations, and at least one Defender crushing by border officials and the Department of Homeland Security.

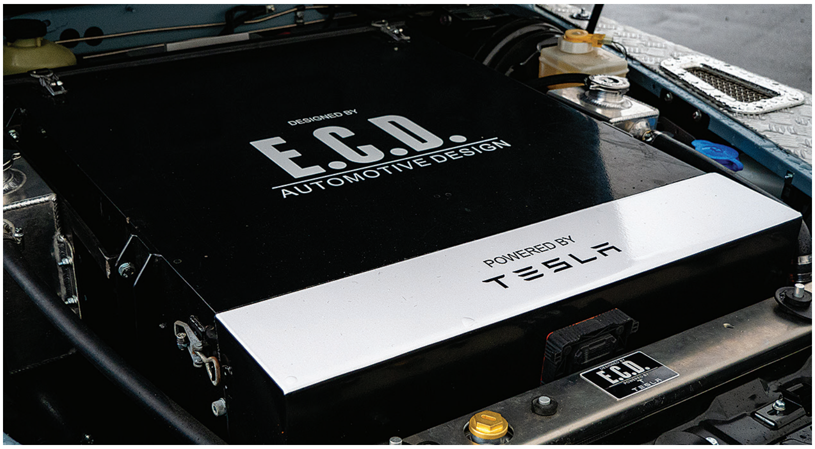
To avoid breaking the law, the Defender you import must be at least 25 years old. But even ratty junkyard specimens are now worth serious money as the starting point for Cinderella-like makeovers. Those taking on such a challenge benefit from the Defender's rust-free aluminum body panels, born from necessity during the steel shortages of postwar England.

Today's love affair with the Defender is just part of a larger craze. Nostalgic 4x4 trucks, including Toyota Land Cruisers and Jeeps, have never been more popular or prized. Ford took advantage with a rock-crawling, retro-tinged Bronco, revived in 2021: Its entire production sold out in advance for two years. And yes, in 2020 Land Rover introduced the first fully redesigned Defender since the Second World War, one so posh and powerful that old-school fans might barely recognize it.

Giving an older Defender an electric power train doesn't alter its charming looks, of course, nor its ability to conquer forbidding terrain. And while restorers are at it, they figure, there's no harm in addressing long-standing design flaws or adding a few modern conveniences.

In an outdoor courtyard at E.C.D., sit a motley group of Defenders and Range





Refurbishment begins with the vehicle's frame, which is stripped, galvanized, and repainted [top left]. Technicians revamp the car's electrical wiring, including the notoriously unreliable 12-volt circuits [top right]. Running at higher voltage is the car's new electric power electronics, originally designed to propel a Tesla [bottom right].The Defender is an outgrowth of Land Rover's original Series 1 model, whose utilitarian lines are evident in this 1954 example [bottom left].

BOTTOM LEFT: LAND ROVER

Rover Classics (an upmarket model that Land Rover introduced in 1969) in various stages of construction. Two scabrous Defender pickups languish at one end, both soon to have their steel frames stripped to bare metal, dipped in molten zinc, and powder-coated. The results could pass for brand-new frames.

Farther down the line are somewhat newer Defender body panels waiting to be refurbished, hand-sanded, and then covered with Ferrari-quality PPG paint. Many customers choose a custom, one-off shade. Wallace recalls a woman tearing a strip of fabric from her dress to use as a color swatch, then accompanying a tech into the paint booth to help spray samples.

Each of E.C.D.'s electric conversions spends about 100 days moving through 20 discrete shop bays, where it undergoes about 2,200 person-hours of meticulous restoration.

In a nearby office, a technician creates interactive animated renderings of ongoing projects, which owners can scrutinize from afar to make adjustments. A dizzying range of bespoke features includes seats upholstered in alligator or ostrich hide, audiophile sound systems, and Warn winches for off-road recoveries.

The buyer of the Defender I test-drove specified a teak-lined cargo area with boxed storage for his ski gear. E.C.D. had to create that yacht-style trim while still maintaining access to the Tesla batteries and cooling system below.

In one work bay, I see the beefy drive unit from a Tesla peeking from the console space between front seats of this

The traction batteries are split, some being housed under the hood and others [shown at left during installation] going beneath the rear seating. The rear of this particular car also includes teak storage compartments [middle]. The result is a superbly restored vehicle, but one that the owner can now plug in [right] rather than fuel up.

E.C.D. AUTOMOTIVE DESIGN

Defender, where the transfer case once lived. This drive unit was designed to send power through two half-shafts to the rear wheels of the Tesla Model S. For this application, the motor is pushed forward and rotated 90 degrees to drive both front and rear Rover axles, with the torque evenly split.

For the Defender application, the single-speed Tesla motor unit required adding a limited-slip differential to divvy power between front and rear wheels, with a 50/50 torque split. The Rover's axles and driveshafts are beefed up to withstand the electric motor's immense power and torque. Project leaders explain to me that there's no need for the low-range "crawl" gear typically found on such vehicles, because Tesla's electric motor provides a whopping 475 newton-meters (350 pound-feet) of torque at zero speed.

The biggest retrofitting challenge is finding space for motors and batteries in cars that were never designed for them—and ensuring the chassis can carry them safely and securely. Richard Morgan, the founder of Electric Classic Cars, says the stars aligned with the Defender: The drive unit fits perfectly between the Rover's frame rails, with just a few millimeters to spare on either side. Fitting the batteries was harder, requiring the fabrication of custom battery cases.

And while safety experts emphasize that EVs are as safe as fossil-fueled cars in crashes, if not more so, customers still want reassurance, Morgan says. His systems look to match OEM safety standards as much as possible, with service disconnects, ground-fault monitors, and layers of redundancy.

Battery boxes use 3-millimeter-thick steel, unlike some electric conversions that use flimsy transparent plastic cases to show off the cells inside—Morgan will have none of that. "If you've got 280 kilos of batteries in a box, that needs to be strong and rigid in an impact," he says.

The original 12-volt electrical system remains, but only to run various low-power accessories. But with no engine to drive belts, Tesla's 400-volt architecture handles the electric motors that provide for power steering, as well as for cooling pumps and the car's A/C compressor.

While such a conversion is plenty challenging, Tesla's electronics have been jailbroken by enterprising hackers, so E.C.D.'s techs have full access to throttle maps, regenerative-braking levels, thermal management, and so forth.

Morgan estimates that salvaged Teslas and other EVs provide about 40 percent of his motors and batteries. The rest are sourced new from Chinese suppliers such as CATL (Contemporary Amperex Technology Co. Ltd.), which manufactures cells that also power new Teslas. With Tesla now building close to 1 million cars a year, conversion companies need only a tiny percentage to crash to fill their warehouses with needed components.

Morgan has heard griping from some purists who call what he is doing a sacrilege. They assert that ripping out a car's internal-combustion guts also tears out its soul. His response: "These are mass-produced classic cars," not seven-figure Ferraris or other models whose stem-to-stern originality is integral to their value. He points out that removing "all the dirty and smelly bits" eliminates the stress, expense, and TLC required by classic cars—including finicky British and Italian cars. "I like classic cars to be used," says Morgan.

To that end, the Rover's original electricals—from Lucas Industries, a company whose founder was sometimes called "the Prince of Darkness" for the notorious unreliability of its products in almost every U.K. car brand—are replaced. Technicians hand-assemble the 23 wiring harnesses required for each conversion. It all looks insanely complicated, but Wallace insists that swapping a fossil-fuel engine is, in many ways, a

bigger headache. Electric conversions are far simpler, he asserts: "This is just a motor, a battery, and two driveshafts."

Morgan and his colleagues freely admit that the environmental benefits of powering a car on electricity are largely an afterthought. "I'm a classic-car guy; I'm not coming at it from the save-the-planet side."

Yet these conversions do have environmental benefits. The most obvious one is zero tailpipe emissions. The more subtle one is giving second lives to two cars—the vintage Rover and the wrecked Tesla from which the motor and batteries came. A typical gasoline family car produces about 24 tonnes of CO_2 over its lifetime, versus 18 tonnes for a comparable EV. Yet about 46 percent of an EV's lifetime emissions are generated during manufacturing, double those of an internal-combustion car. So, keeping that electric hardware on the road for as long as possible, where it can pay off through sharply reduced emissions, is indeed being kind to the planet.

On my test drive, the Rover turns the tables on late-model gasoline SUVs, this ancient truck transmogrified into a speedy tech avenger. Elliot Humble, riding shotgun, notes that every conversion gets 1,000 miles (about 1,600 km) of shakedown testing, all performed by a single technician.

This Defender still steers like a farm implement, but that trait is just part of its boundless charm. The telltale hum of the Tesla motor is louder in this Rover than it is in a Model S, despite the many sound-deadening layers of Kilmat, jute, and carpet that have been added.

But an electric motor makes just a whisper compared with the din of a gasoline engine, let alone the clatter of a Rover diesel. A new air suspension enormously improves the car's notoriously rough ride, and the body barely creaks. The upgraded brakes, a Brembo system with six-piston front calipers, provide plenty of stopping power.

"And it's got modern fuses and relays—things that actually work," Humble says as we ride. "No more glass fuses wrapped in tinfoil to stay on."

For Project Britton, niceties include Recaro seats swaddled in diamond-stitched leather and an Alpine Halo audio system. The appeal is clear: In such status-conscious places as Napa Valley or the Hamptons, a Tesla Model S might as well be a Toyota Camry now. But pull up to the valet line in this whisper-quiet Rover, and you'll draw as much attention as if you had arrived in a Ferrari or a Bentley.

"At the end of the day, it's a toy, isn't it?" Humble says. "We could all get by with a 1.6-liter petrol engine. But it's about having something no one else has."

It's also about having your cake and eating it too—at least for people who can afford the rich frosting. E.C.D. Defenders start from $209,000, and the Tesla-based drivetrain adds roughly $40,000. Add a la carte upgrades, and these electrified dream machines hover around $300,000.

For do-it-yourselfers who choke on those prices, there are less expensive options. Electric GT's Tesla motor-swap system, for example, costs about $40,000 and includes a drive unit, power module, battery-management system, and more. And Electric Classic Cars, in tandem with Super Coopers in Buellton, Calif., is developing a bolt-in conversion kit for vintage Mini Coopers. Like Electric GT's kits, it features connectors-for-dummies that don't allow, say, a positive lead to plug into a negative terminal.

"With an EV, you've got to know more about what you're doing," Morgan says. "If you pick up the wrong end of a 400-volt DC cable, something bad's going to happen. But [with such kits], you don't need special high-voltage knowledge."

Systems can be installed in as little as two days by a pair of experienced technicians—or more slowly by a handy owner with the help of a skilled pal. Such kits are a modern take on the electric conversions that became popular with some enthusiasts starting in the 1970s, before it was possible to buy a new electric car.

Major automakers, which together will be spending hundreds of billions of dollars to evolve into EV companies, may offer such kits themselves in an effort to squeeze as much revenue as possible from that pricey investment. In 2020, for example, General Motors announced it would sell a conversion kit based on the Chevrolet Bolt—although that kit is yet to go on sale.

For now, electric conversions remain a tiny niche in the massive business of restorations and aftermarket equipment. But as EVs mature, the generations that grow up driving them might view today's plug-ins as the classic cars *they* aspire to own, improve, and restore—having no fondness at all for those oil-leaking, exhaust-spewing oddities their grandparents once drove. ■

Pull up to the valet line in this whisper-quiet Rover, and you'll probably get as much attention as if you had arrived in a Ferrari or a Bentley.

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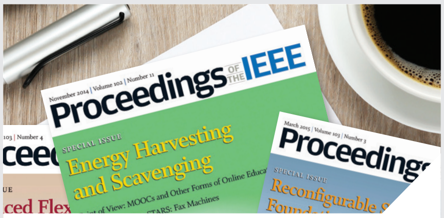

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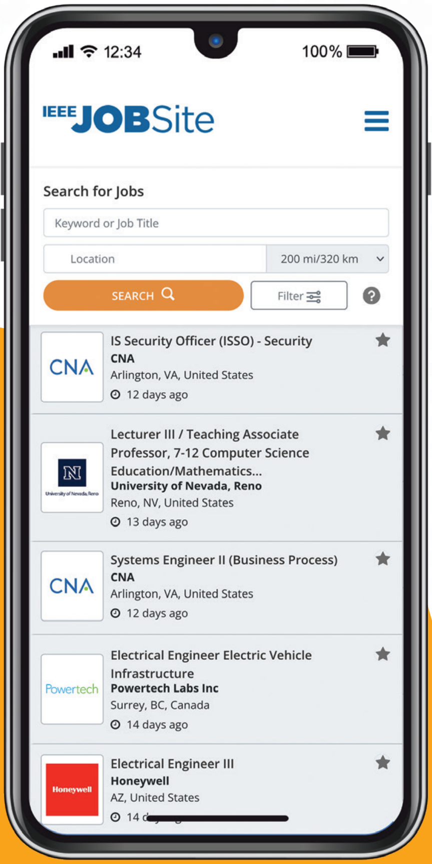

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BY ALLISON MARSH

Past Forward

The German physicist Karl Ferdinand Braun designed this cathode-ray vacuum tube to visually capture the oscillations in electrical circuits.

SCIENCE MUSEUM GROUP

Birth of the Electron

In the wake of Wilhelm Röntgen's discovery of X-rays in 1895, scientists began noodling around with energetic beams and vacuum tubes to see if they could identify the tiny particles that make up atoms. One of those scientists was Karl Ferdinand Braun, who instructed his instrument maker, Franz Müller, to modify a vacuum tube called a Crookes tube by adding a restrictive diaphragm. The diaphragm focused the energy beam, while a phosphor-coated piece of mica created a viewing screen. In a paper published in February 1897, Braun called his invention a cathode-ray indicator tube (like the one shown here), and he described how he had used it to deflect cathode rays with a magnetic coil. Braun's CRT was a forerunner of the oscilloscope, and modified CRTs later found their way into television sets and computer monitors.

Meanwhile, J.J. Thomson, the Cavendish Professor of Experimental Physics at the University of Cambridge, was working on a problem similar to Braun's, using similar instruments. On 30 April 1897, Thomson delivered a lecture at the Royal Institution in London, where he described his experiments to measure subatomic particles he called "corpuscles." Corpuscles are known today as electrons, but did Thomson discover them?

Historians like to argue that last point. Thomson often gets credit, but Braun, for instance, published his results 10 weeks before Thomson's announcement. And, it turns out, several other scientists could reasonably be credited with various aspects of the electron's discovery. ■

FOR MORE ON THE EARLY HISTORY OF THE ELECTRON, SEE spectrum.ieee.org/pastforward-may2022