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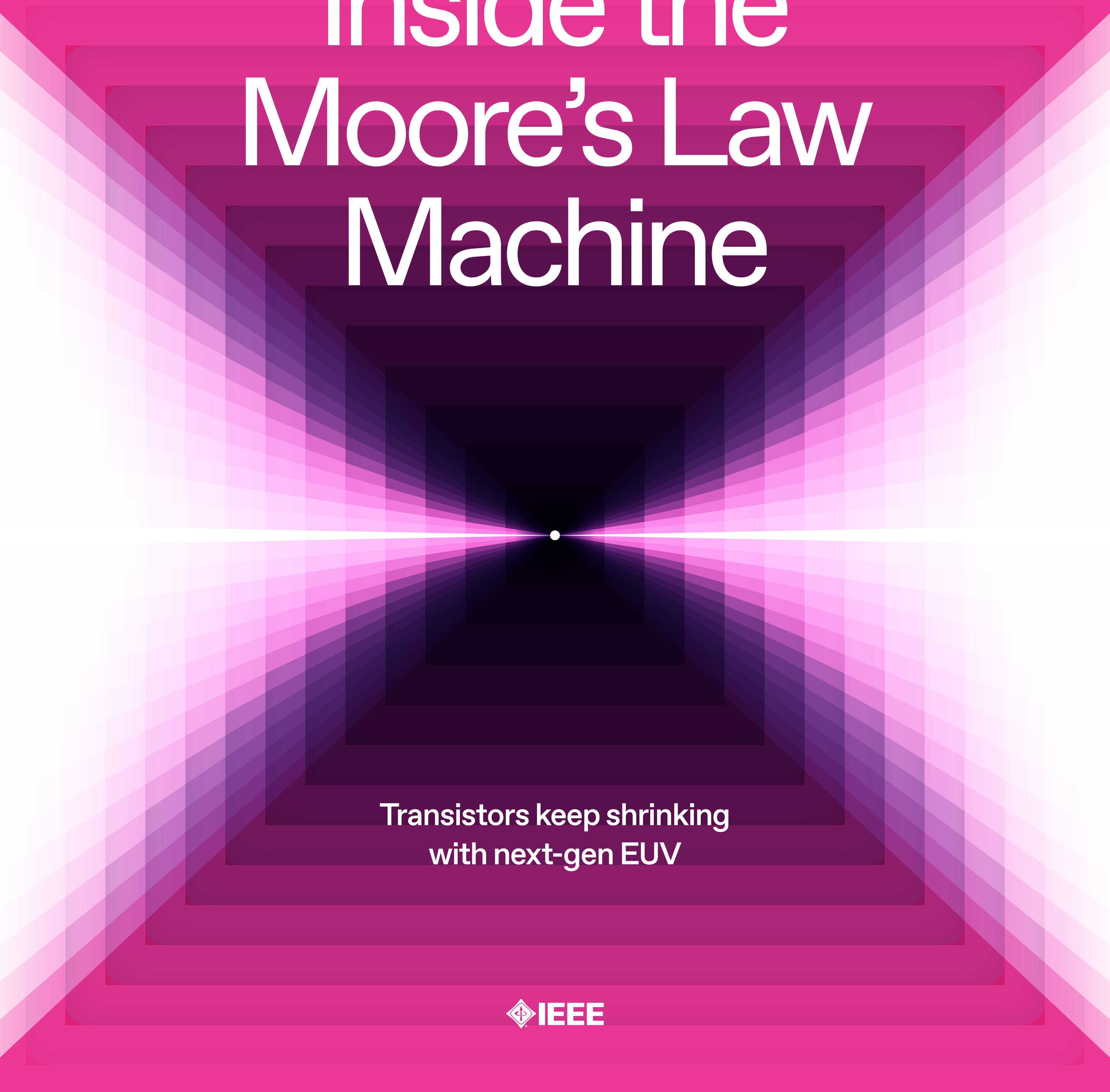

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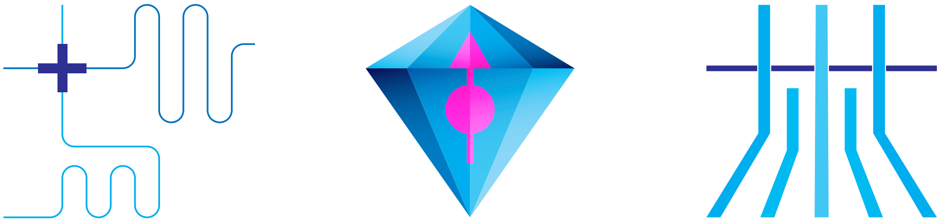

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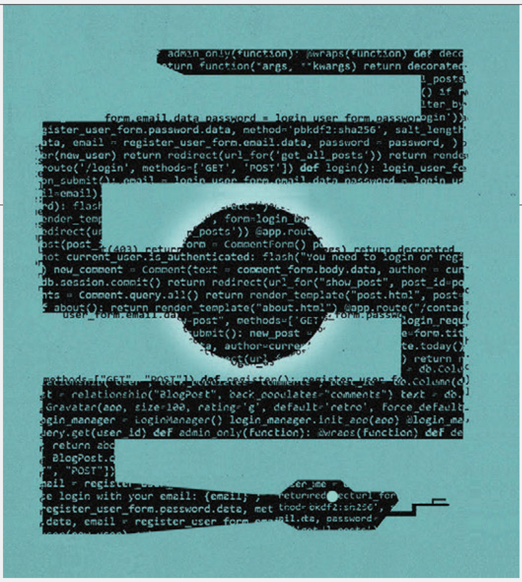
How Python Swallowed the World

Lessons from compiling Top Programming Languages



Programmers seek languages that let them solve particular problems in concise, elegant ways and communicate those solutions to other programmers. For the last 10 years, *IEEE Spectrum* has been trying to help with that search with its annual interactive rankings of the Top Programming Languages, the latest of which is now available on our website by scanning the QR code below.

How we put TPL together has evolved over the last decade, but the basic recipe has remained the same: Find multiple proxies for the popularity of languages and combine them to create meta-rankings. Looking back at the results, we see this recipe has told an interesting tale.

The early years were marked by the introduction and growth of new languages such as Go (first released by Google in 2009) and Swift (first released by Apple in 2014). These languages reflected the shift toward mobile devices and data centers. Later, Big Data drove language popularity, with specialized analysis and visualization languages such as R and Julia coming to prominence.

Then came the defining theme of the last 10 years: the ascendance of Python. Emerging in 1991, at first Python didn't attract much notice, being overshadowed by Perl, another interpreted language released a few years earlier. In any case, no one wrote real programs in interpreted languages. But Python's philosophy of "batteries included"—meaning a large collection of standard libraries—made it easy to use. And Python was easy to adapt to new domains, such as Big Data and AI, the latter thanks to the popularity of new machine-learning libraries like Keras and PyTorch. While compiled languages like C++ aren't vanishing, it's clear that Python is becoming the lingua franca of computing for middle schoolers and Ph.D.s alike.

While compiled languages like C++ aren't vanishing, it's clear that Python is becoming the lingua franca of computing.

Scan the QR code to access the Top Programming Languages online.

Putting together the TPL has also made one other aspect of programming languages clear to us: Computer languages have terrible names.

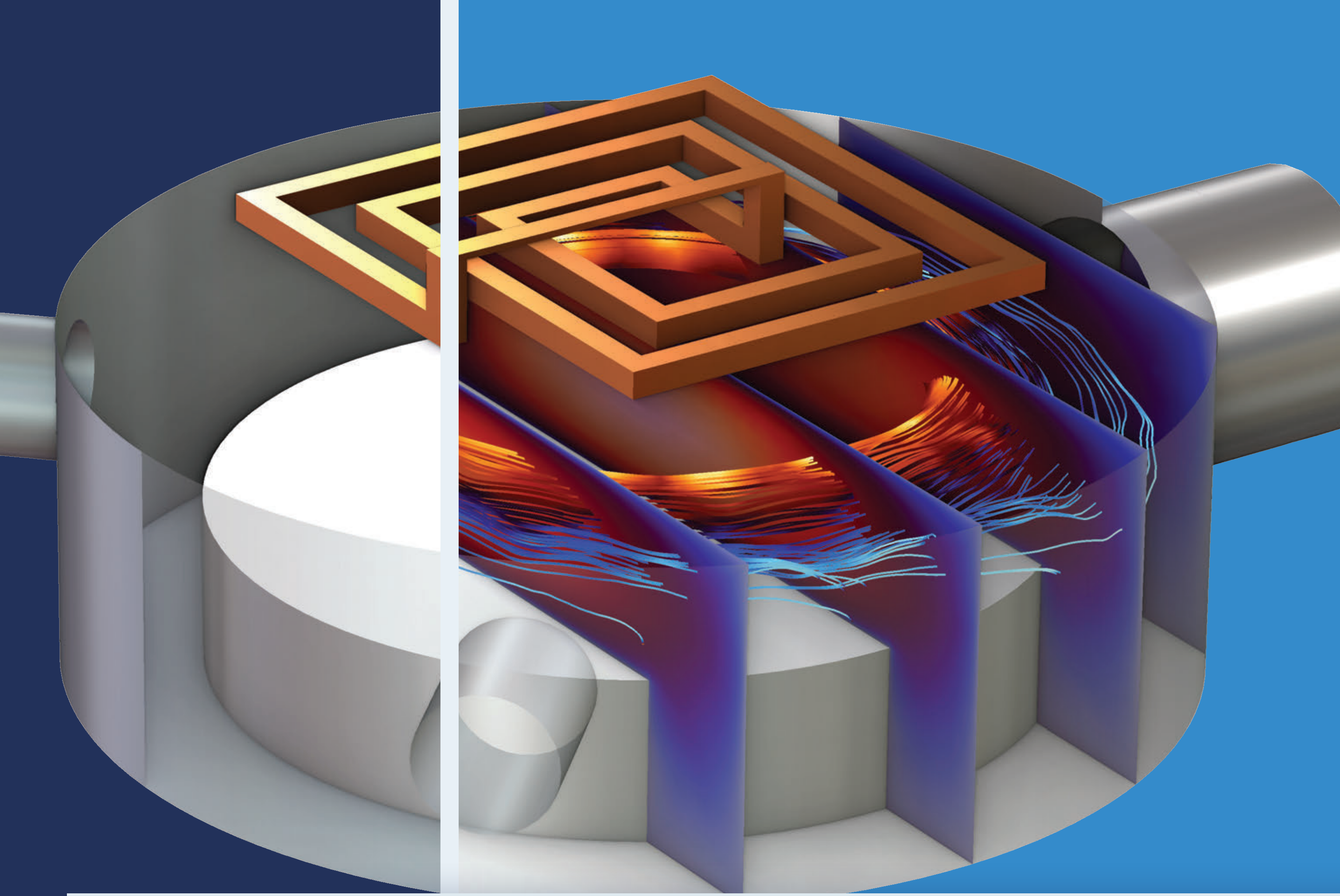
Things started out so well with Fortran and Cobol—brief yet euphonious names rooted in descriptors of language's purpose: formula translator, business language. Sadly, by the late 1960s, the rot had set in. BCPL arrived, its name a brute acronym for Basic Combined Programming Language, four words that conspire to give no information about the nature of the language or its purpose. BCPL begat B. And B begat C. C itself is a staggering accomplishment, a milestone on every timeline of computing. But its name must be considered a stain on its incredible legacy.

For C begat the even greater nominative monstrosity of C++. This made it acceptable to incorporate symbols, a tradition that continued with names like C# and F#. But perhaps even worse is the alternate fashion of just using common nouns as names, for example, Rust, Ruby, and Scheme. Some forgiveness can be given for a borrowed name that's unlikely to cause a semantic collision in normal use, such as Python or Lisp. But there can be none for such abominations as Processing or Go. These are words so often used in computing contexts that not even a regex match pattern written by God could disambiguate all the indexing and search collisions.

Consequently, some of the metrics that compose the TPL require many hours of handwork to clean up the data (hence our strong feelings). Some languages have their signal so swamped by semantic collisions that their popularity is likely being underestimated. So by Lovelace's ghost, if you're naming a language, please suppress impulses toward pun or punctuation. Instead, make it pithy, make it pronounceable, and make it praiseworthy. ■

PORTRAIT BY SERGIO ALBIAC

Illustration by Dan Page



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MATTHIAS MUELLER

Mueller is program manager for offshore hydrogen at Siemens Energy. His coauthor, Roland Dittmeyer, is professor of engineering and director of the Institute for Micro Process Engineering at the Karlsruhe Institute of Technology. Their article describes a project spearheaded by Siemens to design and test the hardware and systems needed to autonomously produce hydrogen from wind energy out at sea [p. 24]. "This is one of the potential ways to turn our way of generating hydrogen around and begin decarbonizing on a massive scale," says Mueller.

JAN VAN SCHOOT

Van Schoot is the director of system engineering at the only company on the planet that makes EUV lithography systems: ASML, located in Veldhoven, the Netherlands. In this issue [p. 44], he describes this crucial chipmaking technology's next step: It required deploying an unusual optics trick that ultimately saved the day. "In an instant, all the pieces of the puzzle fell into place: imaging, throughput, and cost per pixel," van Schoot says.

MICHAEL R. WATTS

Watts is the founder and chief executive officer of Analog Photonics, a Boston-based startup developing chip-based lidar systems. He and his company colleagues, Christopher Poulton, Matthew Byrd, and Greg Smolka, write about their work in "Lidar on a Chip Enters the Fast Lane" [p. 38]. Before founding Analog Photonics, Watts was a professor of electrical engineering and computer science at MIT, where he led the photonic microsystems group at MIT's Research Laboratory of Electronics.

TAMMY XU

A freelance science journalist based in Evanston, Ill., Xu writes in this issue about how AI is improving the accuracy of crop-yield predictions [p. 9]. But high tech hasn't completely replaced low tech, Xu says. Even with the addition of cutting-edge tools like deep learning, to study the interplay between precipitation level, soil quality, and other factors, "the science of crop-yield prediction still requires ancient, low-tech techniques, like looking out the window or observing the color and texture of a sample of dirt," she says.

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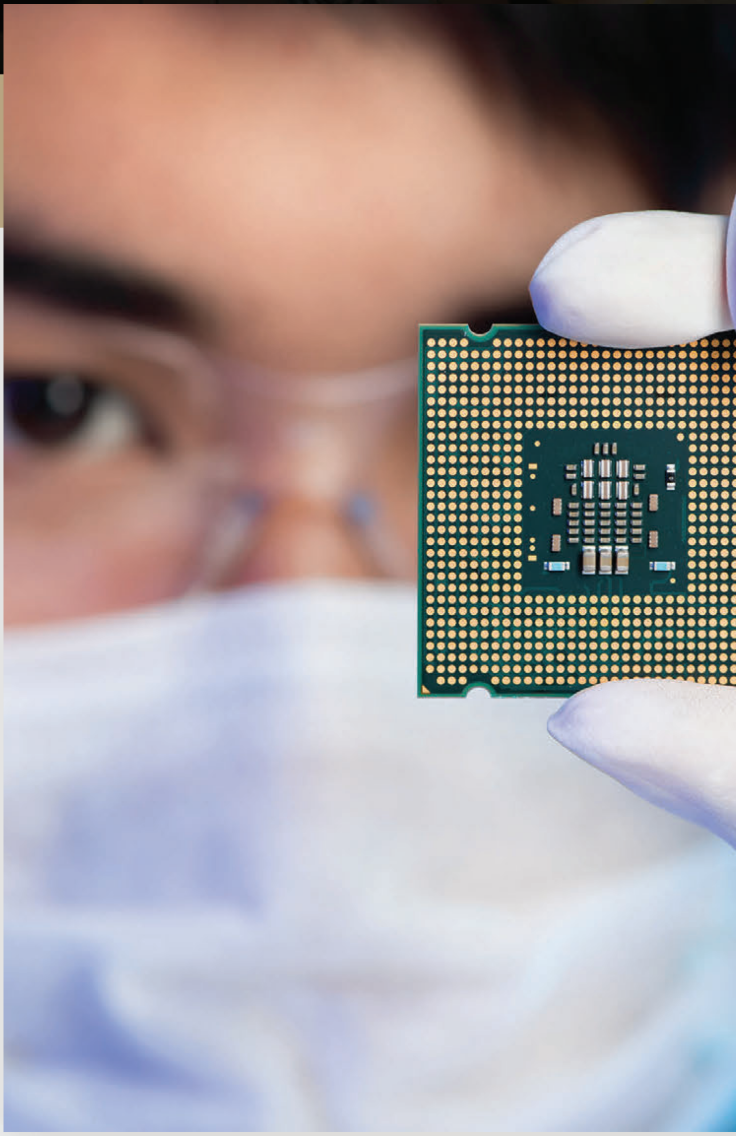

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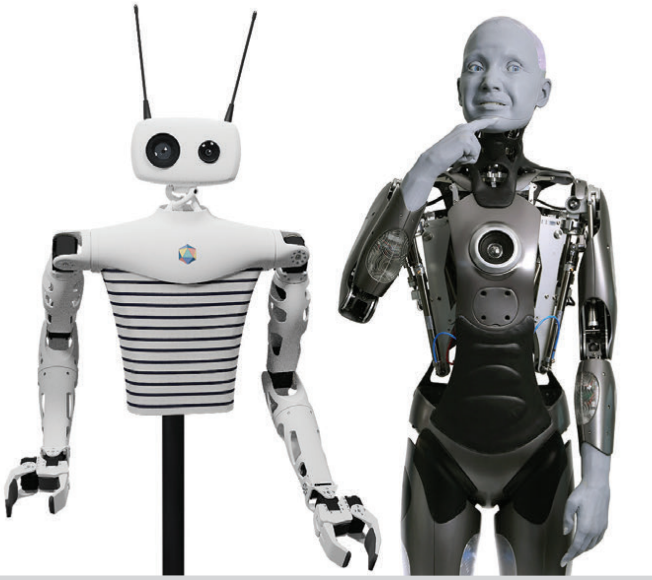

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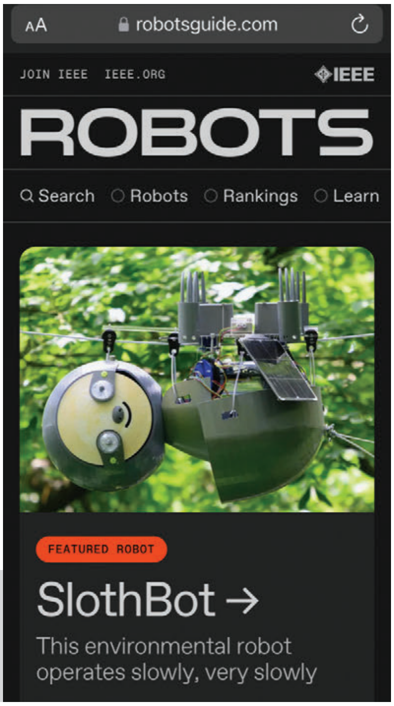

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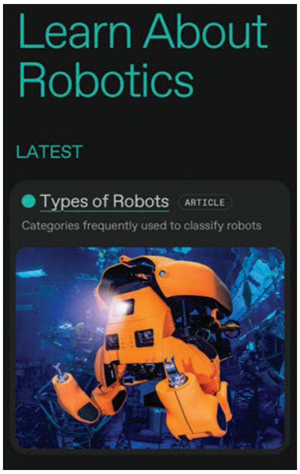

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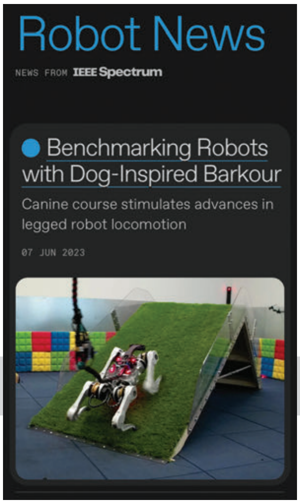

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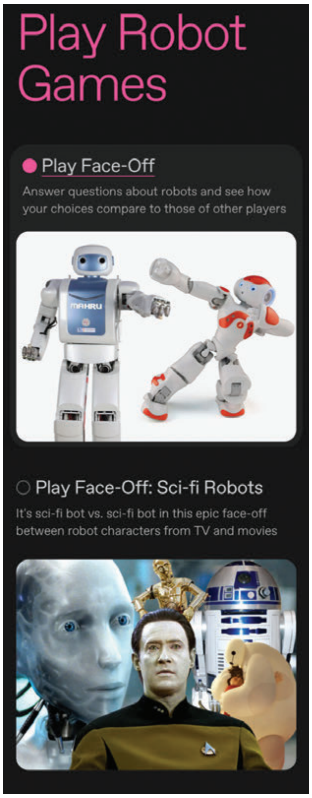

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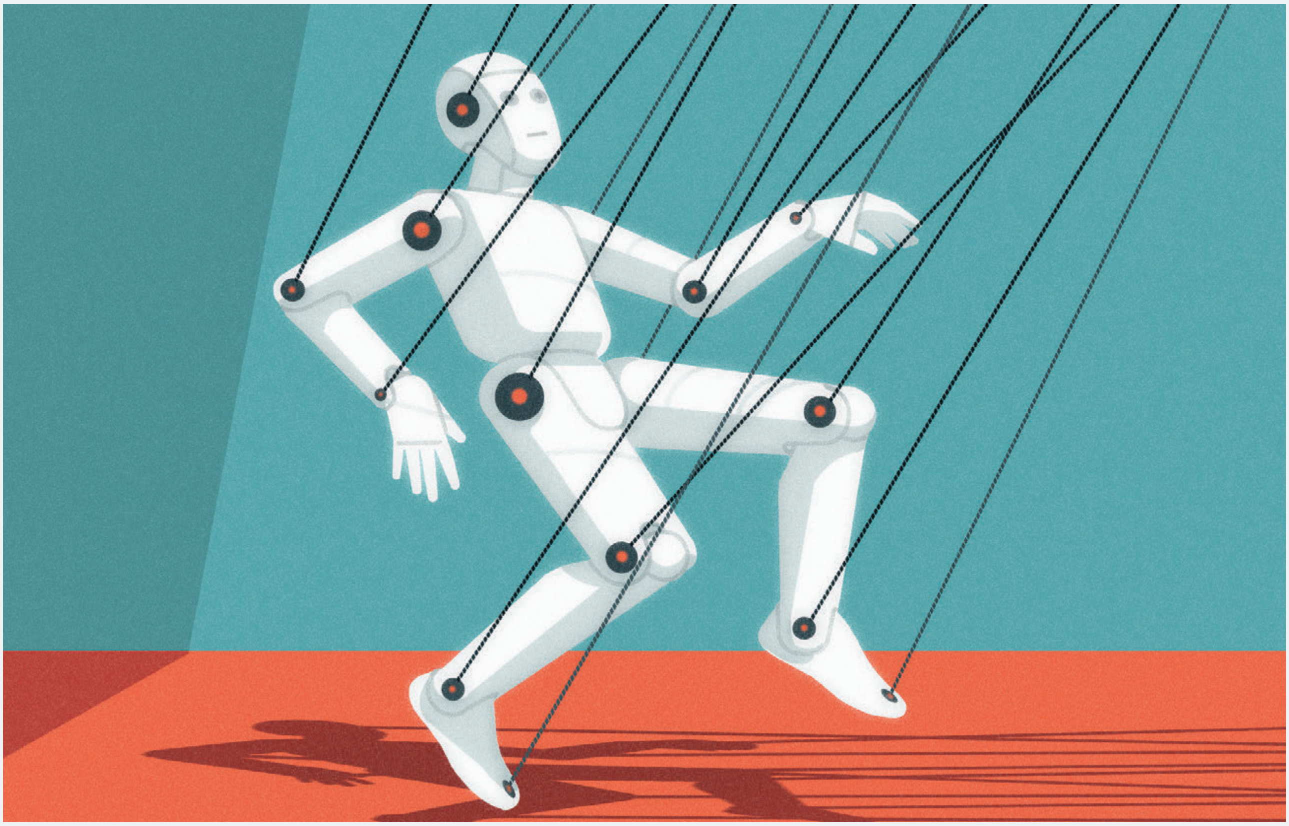


ARTIFICIAL INTELLIGENCE

Europe and China Solidify AI Regulation >

Meanwhile, the U.S. toys with nonbinding blueprints

BY ELIZA STRICKLAND

During the past year, perhaps the only thing that has advanced as quickly as artificial intelligence is worry about artificial intelligence.

In the near term, many fear that chatbots such as OpenAI's ChatGPT will flood the world with toxic language and disinformation, that automated decision-making systems will discriminate against certain groups, and that the lack of transparency in many AI systems will keep problems hidden. There's also the looming concern of job displacement as AI systems prove themselves capable of matching or surpassing human performance. And in the long term, some prominent AI researchers fear that the creation of AI systems that are more intelligent than humans could pose an existential risk to our species.

The technology's rapid advancement has brought new urgency to efforts

Illustration by Dan Page

around the world to regulate AI systems. In April 2021 the E.U.'s European Commission proposed the AI Act, which uses a tiered structure based on risks. AI applications that pose an "unacceptable risk" would be banned; high-risk applications in such fields as finance, the justice system, and medicine would be subject to strict oversight. Limited-risk applications such as the use of chatbots would require disclosures.

In June 2023, the European Parliament voted to advance the draft legislation. But it's not a done deal. Negotiations over amendments to the act are ongoing, with hopes of reaching an agreement on a final text by the end of 2023. If all proceeds apace, the law will take effect two years later.

The E.U.'s moves notwithstanding, China's rule-makers have been the quickest to turn proposals into real rules. In the West, there's a mistaken belief that China isn't concerned with AI governance, says Jeffrey Ding, an assistant professor of political science at George Washington University and creator of the ChinAI newsletter. In fact, he says, Chinese regulations have already been put in force, starting with rules for recommendation algorithms that went into effect in March 2022. To manage generative AI (AI systems that generate text, images, video, and other content), the Chinese government issued early rules in January 2023, and announced further rules in July. Ding says all these regulations stem from a common concern: "The Chinese government is very concerned about public-facing algorithms that have the potential to shape societal views," he says.

China's initial set of rules for generative AI required websites to label AI-generated content, banned the production of fake news, and required companies to register their algorithms and disclose information about training data and performance. The second set of rules requires companies to moderate the content generated with their tools (and specifically to be on the lookout for "illegal content"), improve the accuracy of their training data, and respect intellectual property rights. But Ding notes that these rules apply only to AI systems that are accessible to the general public, exempting systems used by industrial, educational, and scientific entities. Companies may respond by making products that are available only to businesses, he says, "so they don't draw scrutiny from government regulators."

The first gesture toward regulation in the United States was the Blueprint for an AI Bill of Rights, issued by the White House in 2022. It is nonbinding.

Meanwhile, as China and the E.U. have forged ahead with rule-making, countries including Brazil, Canada, and the United States are coming along behind. In the United States, home to many of the companies and labs that are putting forth cutting-edge AI models, the first significant step came in October 2022, when the White House issued a nonbinding Blueprint for an AI Bill of Rights. That document framed AI governance as a civil rights issue, stating that citizens should be protected from algorithmic discrimination, privacy intrusion, and other harms.

Suresh Venkatasubramanian, a computer science professor at Brown University, coauthored the Blueprint while serving in the White House Office of Science and Technology Policy. He says the Blueprint suggests a civil rights approach in hopes of creating flexible rules that could keep up with fast-changing technologies. "By focusing on civil rights, we can articulate protections that are agnostic to the technology being used, whether it's an Excel spreadsheet or a neural network," he says.

Venkatasubramanian notes that there is "broad consensus that we should do something" on the legislative level. And indeed, in June U.S. Senate Majority Leader Chuck Schumer laid out a plan that he said will lead to AI regulations.

Remarkably, some of the calls for regulations are coming from the very companies that are developing the technology. OpenAI's CEO, Sam Altman, recently told the U.S. Congress in written testimony that "OpenAI believes that regulation of AI is essential." Meanwhile, Sundar Pichai, CEO of Google and its parent company, Alphabet, said recently that there will need to be "global frameworks" governing the use of AI.

But not everyone thinks new rules are needed. The nonprofit Center for Data Innovation has endorsed the hands-off approach taken by the United Kingdom and India; those countries intend to use existing regulations to address the potential problems of AI. Hodan Omaar, a senior policy analyst at the nonprofit, tells *IEEE Spectrum* that the European Union will soon feel the chilling effects of new regulations. "By making it difficult for European digital entrepreneurs to set up new AI businesses and grow them, the E.U. is also making it harder to create jobs, technological progress, and wealth," she says.

The course of events in Europe could certainly help governments around the world learn by example.

Connor Dunlop, the European public policy lead at the nonprofit Ada Lovelace Institute, says that one of the most contentious amendments in the AI Act is the European Parliament's proposed ban on biometric surveillance, which would include the facial-recognition systems currently used by law enforcement.

Another hot topic is an E.U. parliamentary amendment that attempts to cover recent advances in "foundation models," which are massive and flexible AI systems that can be adapted for a wide range of applications. "The AI Act is designed as product legislation," Dunlop explains. "The risk is defined by the intended purpose." But that framework focuses on the companies or organizations that deploy the technology and leaves the developers of foundation models off the hook. "What the European Parliament is trying to do is add an extra layer" to the regulation to remedy that, he says.

Any multinational AI company will find it a challenge to comply with myriad local rules unless countries reach global agreements. The intergovernmental political forum known as the Group of 7 nations (G7) has already begun discussing AI governance, and European officials have suggested that companies worldwide could sign on to a voluntary "AI code of conduct." There is no time to waste, said European Commission executive vice president Margrethe Vestager at a recent meeting: "We're talking about technology that develops by the month." ■

The E.U. and the U.K. offer a study in contrasts. The former is regulation-forward; the latter is laissez-faire.

Journal Watch

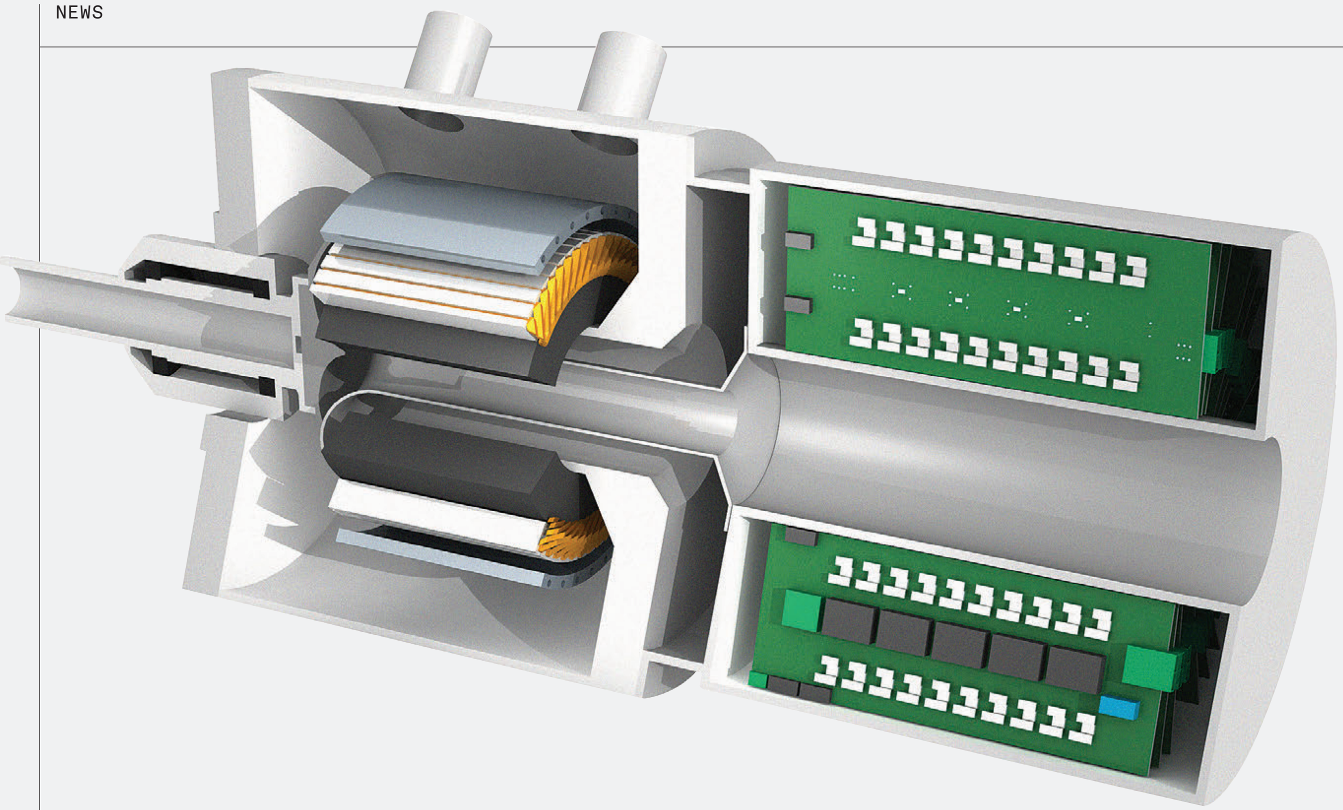
AI's Latest Yield: Where to Expect the Best Harvest

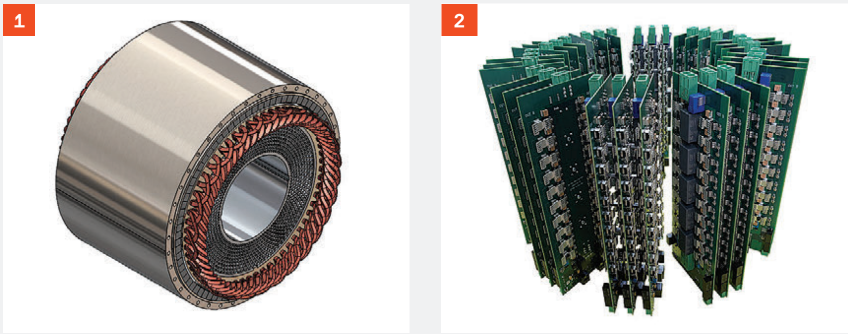

GETTY IMAGES

Researchers from Zhejiang University and the risk-management company Tongdun Technology, both in Hangzhou, China, have demonstrated how using deep-learning techniques can improve crop-yield predictions. Their methods forecast how a crop's harvest will be affected by factors like weather and soil conditions. Accurate predictions are more important than ever because climate change is increasing the risk of low crop yields in multiple regions.

The researchers presented their findings at the 26th International Conference on Computer Supported Cooperative Work in Design, held from 24 to 26 May in Rio de Janeiro.

Deep-learning techniques, they showed, can calculate how variables like precipitation and temperature affect crop yield and also track how they affect one another. Because these methods capture what the researchers call "complex temporal dependencies"—whose impact on crop yield is usually cumulative—this multivariate analysis delivers results that are more accurate than those produced by looking at each variable independently. —Tammy Xu





Researchers at MIT have developed a 1-megawatt electrical motor that could help electrify commercial airliners and lead to new types of hybrid or fully electric aircraft. At top is the demonstrator prototype, including (1) a low-loss, tooth-and-slot stator surrounded by a thermal management system, and (2) 30 custom-built, high-speed power-electronics boards that enable high-frequency alternating current in the stators, thus increasing the motor's rotating speeds.

AEROSPACE

Aircraft Motor Breaks the Megawatt Barrier ›

MIT's new motor gets battery-powered planes ready for takeoff

BY EDD GENT

Aircraft manufacturers aim to slash some of their substantial carbon emissions by electrifying aircraft, but the industry's stringent weight restrictions make this difficult. Building electric motors that match the power-to-weight ratios of jet engines has proven especially challenging, so most efforts have been restricted to smaller aircraft. A new compact, lightweight design for a megawatt-scale motor unveiled by researchers at MIT could open the door to electrifying much larger aircraft.

While the automotive sector is undergoing a transition from fossil fuels to battery power, doing the same in aviation is much harder. The energy density of modern batteries is still far

MIT (2)

Illustration by John MacNeill

too low to power aircraft for substantial distances, which is why companies like Eviation are focused on short intercity hops and a host of electric vertical-take-off-and-landing companies are aiming to disrupt the daily commute.

Batteries may get most of the attention, but they're not the only area where weight is a problem—electrifying the motors has also been a challenge. Electric motors create thrust by passing current through large amounts of copper wiring and steel to create magnetic fields that can turn a rotor. These materials are inherently heavy, says Zoltán Spakovszky, a professor of aeronautics at MIT, and this makes it difficult to build electric motors with a high power-to-weight ratio, also known as specific power.

As a result, the motors used in today's electric aircraft are capable of producing only hundreds of kilowatts of power, which is too little to power larger aircraft. But in research presented at the AIAA Aviation Forum, held between 12 and 16 June in San Diego, Spakovszky and his colleagues unveiled designs for an electric motor capable of generating 1 megawatt of power. They say this achievement will bring the electrification of regional jets within reach.

The MIT team's design features a circular drum—the rotor—with an interior surface lined with permanent magnets. The magnets are arranged so that the motor can do without the heavy layer of steel that is usually necessary to concentrate the magnetic fields generated when the motor receives power; instead, it uses relatively lightweight titanium. Sitting inside the rotor is an incredibly compact stator design that helps boost electrical efficiency. It's a cylindrical piece of steel with an outer surface covered in protruding "teeth." These teeth are covered in densely coiled copper wires. Passing a current through these wires generates a strong magnetic field, which interacts with the permanent magnets on the rotor to spin the drum around and drive the motor.

The design also features a high-speed power electronics system made from 30 custom-built circuit boards. The boards make it possible to alternate the currents in the stator at an incredibly high frequency and therefore significantly increase the speed at which the motor rotates.

The researchers have yet to assemble their device, but they have tested all of the major components and demonstrated in simulations that it will be able to reach the expected power levels. When fully assembled, the motor will weigh 57.4 kilograms, which equates to a specific power of 17 kilowatts per kilogram, considerably more than the 13 kW/kg that previous research from NASA identified as necessary to power large electric aircraft.

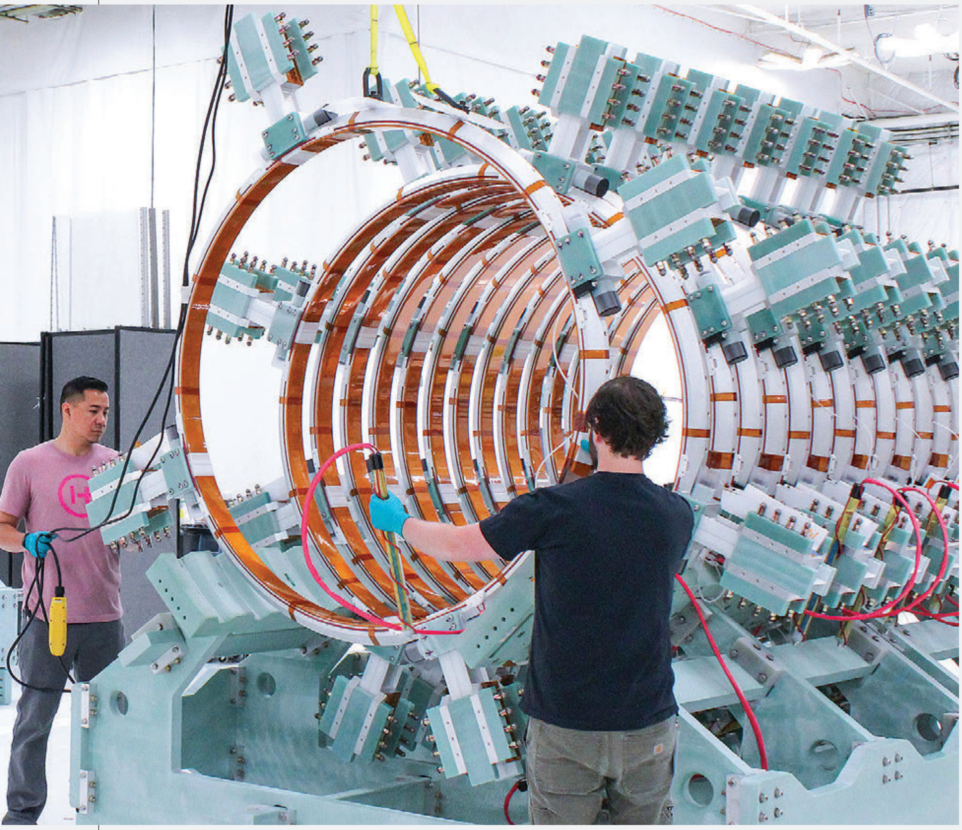
> **"There is no silver bullet when it comes to achieving the required paradigm shift in specific power. Many things together make the design possible, and the devil is in the details."**
>
> —ZOLTÁN SPAKOVSZKY, MIT

Getting there wasn't simple, says Spakovszky. "There is no silver bullet when it comes to achieving the required paradigm shift in specific power," he says. "Many things together make the design possible, and the devil is in the details."

One of the most critical elements is the way the team dealt with thermal management. Producing 1 MW of power generates roughly 50 kW of heat, says Spakovszky. "Think of a car engine revving at full power and turning all the work into heat," he says. "Or consider 500 incandescent 100-watt lightbulbs burning inside a space equivalent to a small beer keg."

The MIT team's design features a novel air-cooled heat exchanger made from aluminum alloy that sits inside the stator. The cylindrical structure features a honeycomb of small air channels, whose complex geometry requires that it be 3D printed. But the design enables the team to achieve cooling efficiency close to what you would get with a liquid system, says Spakovszky, while maintaining the required structural integrity.

"It's great to see the progress being made by MIT," says Kiruba Haran, a professor of electrical and computer engineering at the University of Illinois Urbana-Champaign. Haran's group is also developing a megawatt-scale electric motor, as are teams at Ohio State University and the University Of Wisconsin–Madison. And they could have an impact on aviation relatively soon, says Haran, even if battery technology takes time to catch up. Fossil-fuel alternatives like hydrogen and ammonia are likely to rely on fuel cells that convert chemical energy to electrical energy, and will therefore require electric-propulsion systems. And hybrid systems, in which electric motors are integrated with gas turbines to allow battery-powered operation for parts of the flight, could come even sooner, says Haran. ■



Staffers at Helion Energy put the finishing touches on a section of the latest iteration of the company's Polaris prototype fusion reactor.

HELION ENERGY

ENERGY

Welcome to Fusion City, U.S.A. › Everett, Wash., has the world's highest concentration of fusion startups

BY MARK HARRIS

In an anonymous office park in Everett, Wash.—the town best known as the home of aviation giant Boeing—startup Zap Energy is trialing a prototype reactor that is already producing high-energy neutrons from nuclear fusion, if not yet enough to send power back into the grid.

Less than two miles away, Helion Energy has its own facility, purchased from a Boeing contractor and housing its own operational fusion prototype built in part by aerospace veterans.

Since going active last summer, Zap's FuZE-Q prototype has housed thousands of fusion reactions, each generating reams of data as Zap gradually ramps it up toward the temperatures, plasma densities, and reaction times necessary to generate more power than it consumes.

Zap's eventual commercial fusion reactor, intended to reliably produce enough power for 30,000 homes, will be no larger than the office-desk-size prototype, except for the addition of a liquid-metal "blanket," heat exchangers, and steam turbines to turn its energetic neutrons into electricity. The core reactor will be shorter than a Mini Cooper.

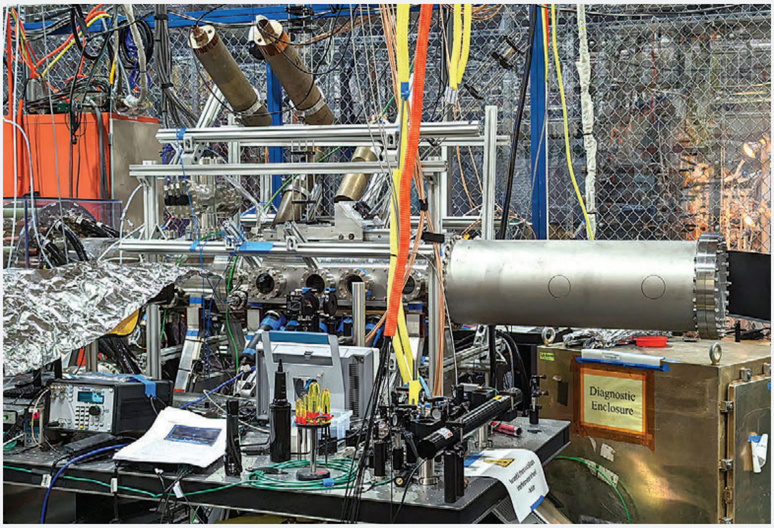
This minimalist take on fusion is in complete contrast with the city-block-size Iter megaproject currently taking shape in southern France. By the time that long-delayed, publicly funded reactor goes live, it will be 30 meters tall and weigh more than 18 Mini Coopers. It will also have cost China, the European Union, the United States, and other partners over US $22 billion. (Helion's reactor will be only slightly bigger than Zap's, about two meters tall and 12 meters long.)

"The two main drivers of cost are complexity and size," says Derek Sutherland, Zap's senior research scientist. "Zap excels at reducing both of those because the system has no cryogenics, no superconducting coils, no auxiliary heating, and no magnets."

The core principle of fusion is to increase the ions' kinetic energy until they're moving fast enough—that is, they're hot enough—to overcome their mutual electrostatic repulsion, then collide and fuse. Iter's reactor is a traditional tokamak design that aims to ignite a burning plasma 10 times as hot as the sun. The reason for its gargantuan size is simple: The larger it is, the more power it will produce.

But a crucial balance must be struck: The faster and hotter the ions, the harder they are to confine. Keeping Iter's fusion reaction going will require an immense battery of cryogenically cooled superconducting magnets.

Instead of trying to coax a continuous fusion reaction to life, as Iter does, Zap and Helion find it simpler to string together short pulses of fusion activity. Zap's process manipulates deuterium



Zap Energy's FuZE-Q fusion reactor prototype has already done tens of thousands of fusion pulse tests. The data gleaned from all those pulses will inform the development of Zap's commercial reactor.

(an isotope of hydrogen) plasma, using magnetic forces to pinch it into a tight fractionating column reminiscent of the distillation columns used to separate crude oil into distillates such as gasoline and kerosene. The different layers of the deuterium plasma flow at different speeds, keeping the plasma stable and generating high-energy neutrons until it collapses.

Helion will fuse deuterium with helium-3, an isotope of helium so scarce that some experts have even suggested mining it on the moon. Polaris, Helion's seventh-generation reactor prototype, however, should be able to produce its own helium-3 from deuterium, and Helion claims it has already generated a small amount. The deuterium–helium-3 reaction produces relatively few neutrons. But that isn't a problem, because Polaris produces electricity directly from the fusion reaction instead of boiling water to produce steam. Each fusion pulse should cause the plasma to expand, increasing its magnetic flux and inducing electric current in the magnetic coils. That current ultimately flows back to the huge bank of capacitors that provide the energy to start the fusion reaction.

Both Zap's and Helion's fusion reactors rely on capacitors. Zap's capacitor banks will store 1.5 megajoules of energy; Helion's will store a staggering 50 MJ.

While Zap has set five to 10 years as a realistic timetable for power generation, Helion has already sold 50 megawatts of power to Microsoft, for delivery in 2028.

Helion expects to complete the assembly of its last prototype Polaris by January 2024. The reactor will then gradually increase power and compression through the year. "If all [proceeds] the way we expect, we should be able to recover enough electromagnetic energy from the fusion system to recharge those banks plus a little bit extra," says David Kirtley, Helion's founder and CEO. "And that little bit extra is net electricity." ■

MARK HARRIS

TELECOM

5G's Growing Pains › So far, the reality hasn't lived up to the vision

BY MICHAEL KOZIOL

By now, the cellular industry's rollout of 5G networks is three or four years old. And although 5G networks are continuing to deliver better and faster service than 4G in general—compared with 5G service from a year ago—the networks' upload and download times have generally declined. That's according to speed-test data from network diagnostics company Ookla. Even the most robust 5G networks are barely cracking 1 gigabit per second. The aspirational 5G download speed of 20 Gb/s originally cited by the International Telecommunication Union is still just that—aspirational.

"You're never going to see that kind of performance," says Mark Giles, an industry analyst at Ookla. "That's like with as much spectrum bundled together, in a highly capable device, totally stationary, no one else on the cell, clear day with the perfect conditions."

5G is facing the same problem had by its predecessors—normal growing pains as more customers buy new phones and other devices that can tap into these networks. "You look to 4G and we had the same," says Giles. "So, with initial deployments of 4G, there was a lot of capacity to soak up those early users. And then as more and more users come on, that capacity gets used up."

Giles points out that most network operators began their 5G rollouts by building on top of the existing 4G network's core infrastructure. While non-stand-alone 5G isn't expected to perform as well as the alternative—stand-alone 5G—it is much cheaper and easier to deploy because it doesn't have to be built out from scratch.

This strategy has hampered 5G deployments because operators are lim-

HARRY CAMPBELL/ISPOT

ited to building 5G networks wherever they have existing cell towers and other infrastructure. But cost isn't the only factor. There are also regulatory and permitting problems—particularly in dense urban areas—that make finding a spot to put a new cell site the biggest challenge.

Outside of cities, there's a different problem. The millimeter-wave band (30 to 300 gigahertz), a big selling point for 5G, can support lower latencies and greater data rates. The caveat for all higher frequencies, however, is that signals don't travel particularly far. That's great for cities, less so for the suburbs or rural areas. As more people in more places start using 5G networks, network performance, in aggregate, is diminished because of that fact.

"I think what this degradation is really highlighting is the disconnect between the vision for these Gs and what's actually on the ground," Giles says.

Because of attenuation and other challenges, millimeter-wave has seen barely any uptake outside of a handful of countries, including the United States, and even there it has been limited. Companies like Verizon—initially bullish on millimeter-wave—have instead pivoted to other newly available bands, most notably the C-band (4 to 8 GHz).

As of 2022, "140 operators in 24 countries have millimeter-wave licenses," says Giles, citing data from the Global mobile Suppliers Association (GSA). "But only 28 in 16 countries are actually deploying it. So it's a small group of operators actually going after it."

Millimeter-wave is seeing some limited use in areas that have massive congestion—think sports stadiums and airports. But failing to build out millimeter-wave as a broader backbone component of 5G networks, regardless of whether because it's too expensive or technically limited, hasn't helped 5G through its periods of growing pains.

What's more attainable is what the ITU has set as the "user experienced data rate," which the organization said should be 100 megabits per second down and 50 Mb/s up. By that metric, median 5G network experience in many countries—despite speeds having degraded in the past year—still meets the ITU's benchmark.

The aspirational download speed of 20 Gb/s originally cited by the International Telecommunication Union is just that—aspirational.

According to Ookla's speed tests, there are a handful of countries bucking the trend in performance degradation: Canada, Italy, Qatar, and the United States. That said, Giles doesn't believe that means there's necessarily any common denominator among them.

In the United States, Giles suggests, more availability of new spectrum has so far helped operators stay ahead of growing congestion on the new networks. In Qatar, by contrast, the massive investment around the 2022 FIFA World Cup included building out robust 5G networks.

It's too early to say whether or how 6G development will be affected by 5G's early stumbles. One possibility is that the industry would devote less time to terahertz-wave research and instead consider how cellular and Wi-Fi technologies could be merged in areas requiring dense coverage. ■

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England's Fission Quest

By Willie D. Jones

After a three-decade gap, during which nuclear power fell out of favor, the United Kingdom is working toward commissioning a new nuclear power station. In February 2023, this 450-tonne reactor pressure vessel was ferried along the River Parrett to Combwich Wharf, in Somerset, England, then moved to the nearby site where the Hinkley Point C nuclear power station is being built. When completed, the power plant will generate 3,200 megawatts, enough to meet roughly 7 percent of the U.K.'s electricity demand. But this construction milestone notwithstanding, the project is already several years behind schedule, and billions of pounds over budget.

PHOTOGRAPH BY BEN BIRCHALL/PA IMAGES/GETTY IMAGES


PLAN N° : OUTPER/NCR0008
REF : SM-ER-OU-CR-PROL
MASSE : 2250 KG / 4959 LBS
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ALPHATRON
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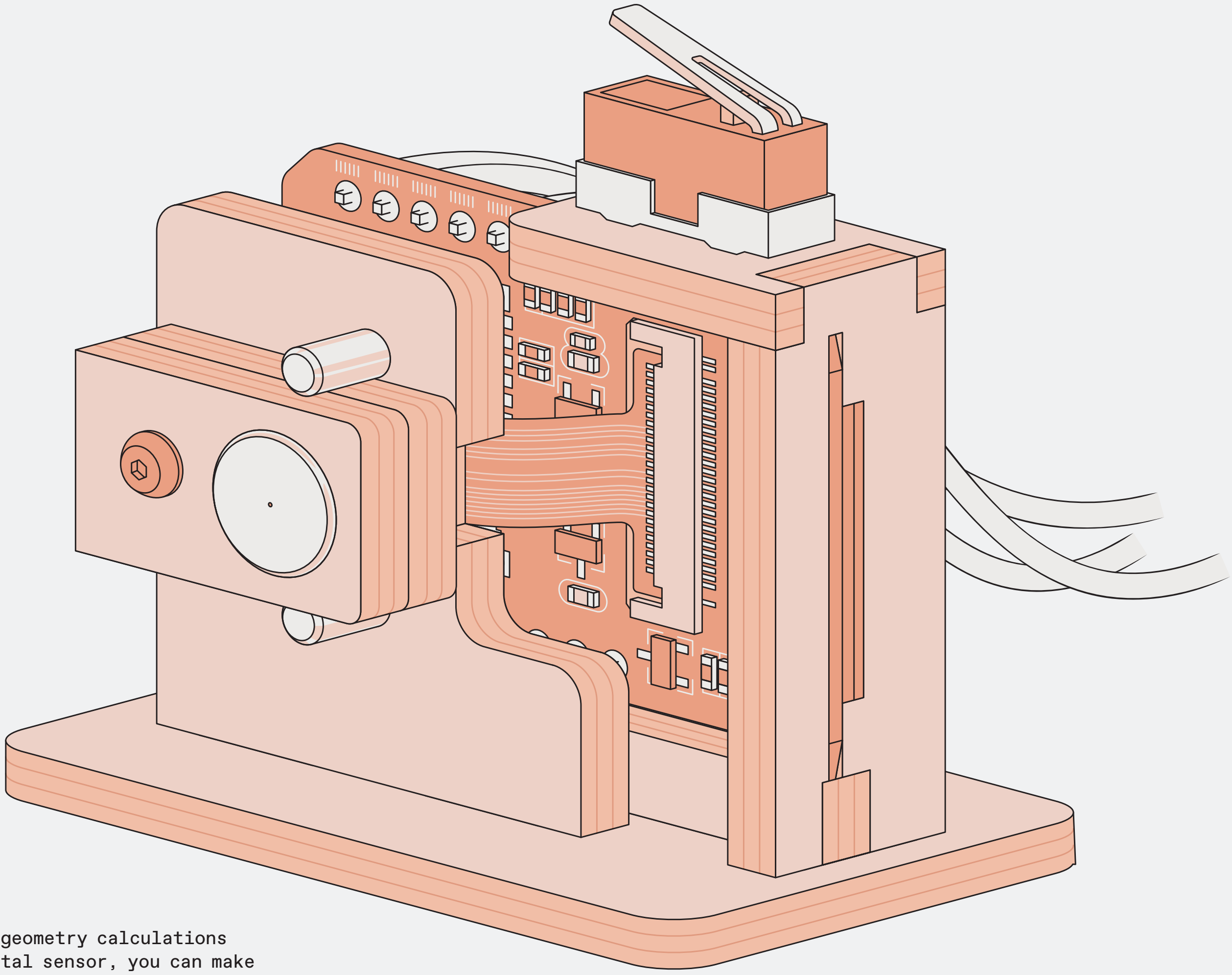
Hands On



With some geometry calculations and a digital sensor, you can make a pinhole camera fast enough to be a point-and-shoot.

Pinhole Photography Goes Digital › Lensless photography without the hassle of film

BY DAVID EHNEBUSKE

My home of Port Townsend in Washington is a community full of arty types and makers. Calls to participate in local cultural activities are not uncommon, but when I saw one for a pinhole-camera photography contest it caught my eye. I'd played with pinhole cameras many years ago, and I wondered if the electrotech skills I'd accumulated since then could be used to improve upon the traditional pinhole camera, while retaining its unique characteris-

Illustrations by James Provost

tics. Could I make a homebrew digital pinhole camera?

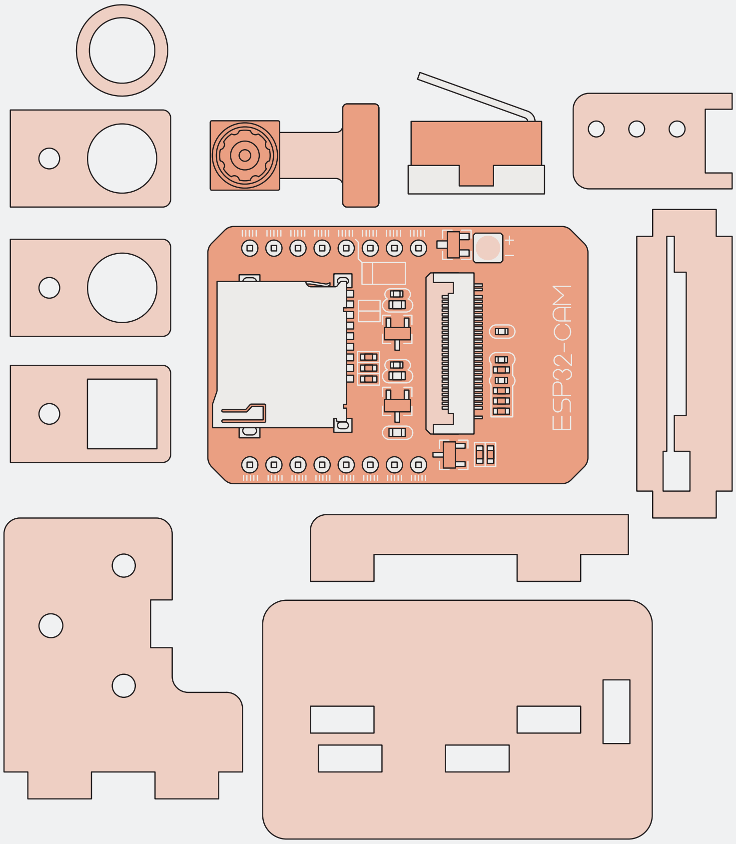
Optically speaking, pinholes have some compelling characteristics that lenses can't match. For one, a pinhole camera has an effectively infinite depth of field: Everything in its field of view is in focus, regardless of how near or far any object is. And there are no distortions, such as chromatic aberration, that are produced by lenses. Recent years have seen an increase in interest in pinhole photography, with international photography events and a variety of cameras being sold commercially or offered as kits.

On the downside, both off-the-shelf and kit cameras use film or photographic paper. The cost of buying and developing film quickly adds up, and of course there's a long delay between taking a photo and seeing the results. Perhaps most significantly, taking photos with a film-based pinhole camera requires long exposure times—typically several seconds even in bright sunlight—increasing the chance of a shot being ruined by unwanted motion.

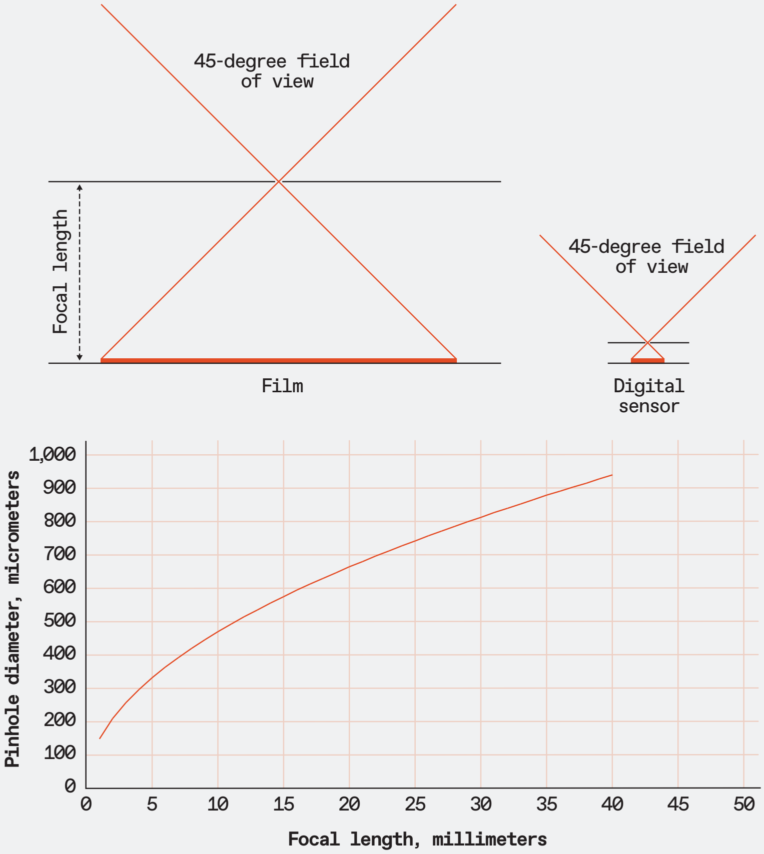
My hunch was that using a digital sensor would solve both these problems. I had a US $10 ESP32-CAM board left over from a previous project that I realized would be perfect for this endeavor. The board integrates the popular Wi-Fi–enabled ESP32 microcontroller with a microSD card socket, an indicator LED, and an interface for a number of low-cost image sensors. I used an OV2460 camera module, which can support a maximum resolution of 1,600 by 1,200 pixels when used with the ESP32-CAM. I removed the OV2460's lens to expose the image sensor.

I wired up a microswitch to one of the board's general-purpose input/output pins and wrote some firmware to use the switch as a shutter control and save images to the microSD card. I also programmed the indicator LED to blink out some error codes in case something went wrong, such as trying to write to a full microSD card. Writing this glue code didn't take long, thanks to the large number of software libraries available for the ESP32-CAM.

I made a wooden case to hold the sensor, ESP32-CAM board, and the shutter switch using my Glowforge laser cutter. The critical pinhole assembly can be detached, allowing me to adjust the focal length—and hence the field of view of the camera—by swapping out different assemblies. This brings the flexibility of detachable



The frame and pinhole lens attachments are made from laser-cut pieces of wood. These hold the microcontroller board [center], image sensor, and the microswitch that acts as a shutter control [top center].



Not all pinholes are the same. Traditional pinhole cameras have relatively long focal lengths because of the size of a frame of film, allowing for larger and easier-to-make pinholes. Because digital sensors are much smaller, a shorter focal length is required, demanding in turn a much smaller pinhole.

lenses to pinhole photography, another nice bonus!

However, nothing comes for free. Pinholes do vary in size, and the trade-off for all these digital advantages is that you have to fabricate a camera pinhole with a smaller diameter than you can get away with in a traditional pinhole camera. This is because the sensor is much smaller than a frame of film: 4 millimeters wide for the sensor versus, say, 35 or 120 mm for film. Consequently, to ensure the complete image created by the pinhole falls onto the sensor's surface, the sensor must be much closer to the pinhole than with film. When you calculate the optics needed for that arrangement, the result is a smaller hole.

The photos retained the luminous look of traditional pinhole photography.

If I was mass-producing this camera, the go-to process would be chemical etching. Once you dial in all the parameters you can precisely make very small holes all day long. But the time and effort involved in setting up an etching process meant I wanted to find another way.

My first solution was get a thin piece of brass and make a dent in it with a center punch. Then I sanded off the brass from the other side until I just broke through to the dent. This made a nice tiny little hole, but it was a lot of work, and I knew I'd want a few pinholes on hand as I tested the camera.

So I went back to basics and tried stretching some aluminum foil and piercing it with a needle. Normally, this would result in a hole that is far too large. However, I discovered that if I put the foil down on the plastic surface of my work bench, and pressed the needle gently into the foil, the plastic would allow just the very tip of the needle to penetrate the foil. Although not tremendously reliable, this method lets me make a lot of pinholes quickly and check them to find the ones with the ideal diameter.

Then it was time to try out the camera, so I took it out to a local lighthouse and hooked up a battery. The sensitivity of the image sensor means that the exposure time required is only a fraction of second, and I was able to download my photos from the microSD card and check them right there on the shore. Yet the photos retained the luminous look that's characteristic of traditional pinhole photography. Success!

An obvious improvement would be to coat the inside of the interchangeable optical assemblies with some matte black material, as internal reflections add some fuzziness to my photos. Another would be to add an LCD screen so that you could view exactly what the camera is seeing in real time—the ESP32 controller has more than enough spare compute power to drive a small display.

Meanwhile, I'm still waiting to hear how I did in that photography contest! ■

BY DANIEL P. DERN

Careers:
Brij Singh

Electrifying John Deere's heavy-duty vehicles

Brij Singh displays the inverter that powers the electric motor used in John Deere hybrid loaders.

JOHN DEERE

For Brij Singh, electrifying John Deere's heavy-duty vehicles reflects his past. Singh grew up on a farm in India, and is committed to bettering agriculture's future. John Deere, headquartered in Moline, Ill., is a leader in agricultural, construction, forestry, and turf-care machinery. Singh, a power-electronics engineer, has been working to replace the internal combustion engines used in the company's equipment with hybrid (diesel-electric) and all-electric versions.

"Power electronics and electrification of agricultural equipment can help change our world for the better by reducing the equipment's greenhouse gas footprint; providing food and fiber to feed, house, and clothe the world; and helping farmers stay profitable," Singh says.

Singh grew up on a 10-hectare farm his family has owned for more than six centuries in Shahpur Charki, a 560-person village in the state of Uttar Pradesh, India.

"I come from a long line of farmers. I personally know how important [farming] is," he says.

In 2007, he joined John Deere's electronics-solutions group, in Fargo, N.D., as a staff engineer. Three years ago, he moved from his technical role to a more tactical role, taking on the newly created position of external relationships manager. He is responsible for securing government funding to carry out the company's R&D work in Australia, Canada, New Zealand, and the United States. He also helps establish collaborations with academic research groups to work on emerging technologies that could be used to create new products.

Singh enjoys the broader scope and added responsibility of his current job. "I'm now involved with deciding the kinds of vehicles to work on, technologies and components to design and test, and timelines," the IEEE Fellow says.

56
tonnes

WEIGHT OF JOHN DEERE'S 944K HYBRID WHEEL LOADER, WHICH CAN HOLD A LOAD OF UP TO 7.65 CUBIC METERS

Earlier in his career, Singh helped Deere begin the transition away from diesel engines. As a staff engineer from 2007 through 2011, he led, managed, and contributed to the design, development, and deployment of electrification technologies. Inverter technology that he developed has been used in John Deere's 644K and 944K wheel loaders since 2012. Inverters allow a machine's power train to run power between the electrical machines, acting like a generator or motor, and they convert electricity from AC to DC and back again.

Wheel loaders have front and back booms and buckets that move soil, sand, rocks, and other materials. The 944K model weighs more than 56 tonnes and has a bucket capacity of up to 7.65 cubic meters.

During Singh's time as a postdoctoral fellow at the École de Technologie Supérieure, at the University of Quebec, in Montreal, his research involved an indirect-current control technique to reduce harmonics created when different AC waveforms (voltages and frequencies) would create component-damaging heat; the system he developed kept the voltage free of harmonic distortion. Singh's work is generally being used in non-Deere applications, such as a battery-charging system connected to distributed energy resources like solar, wind, and diesel generators.

Moving from diesel to hybrid and all-electric industrial vehicles offers many benefits, Singh says. For the operator, the machines are significantly less noisy and easier to control. For the owner, the vehicles reduce costs because they have greater fuel efficiency and less tire wear, and they require fewer repairs. They also emit less greenhouse gases, which is both a company goal and increasingly mandated by governments.

Like the automotive industry's move to hybrid and all-electric vehicles, the industrial-machine transition requires new designs, software, and materials to be developed and tested. That was Singh's job when he joined the company's advanced power-electronics department in 2011 as a senior staff engineer. He worked on high-efficiency electronics systems, including wide-bandgap power-conversion technologies for EV inverters.

Semiconductor devices made with wide-bandgap materials such as silicon carbide (SiC) and gallium nitride (GaN) can operate at much higher voltages, temperatures, and frequencies than traditional silicon devices can. These materials allow components like inverters to be smaller and more energy efficient, Singh says.

To accelerate Deere's electrification evolution, from 2015 through 2021, Singh and his group collaborated with researchers from the U.S. Department of Energy's National Renewable Energy Laboratory to develop a 200-kilowatt, 1,050-volt silicon carbide inverter, which is now used in the 644K and the 944K. The collaboration with NREL led the company to receive funding through a U.S. government program to reduce greenhouse gas emissions.

Singh says his current job of securing government funding and establishing relationships with university groups is necessary in research areas where the company lacks the expertise, time, and resources.

"Government funding helps the company pursue research and innovation significantly sooner," he says. "Without it, we might have to postpone our efforts another 5 to 10 years. With it, innovation is accelerated in developing and adopting new technologies."

> **"Power electronics and electrification of agricultural equipment can help change our world for the better by reducing the equipment's greenhouse gas footprint and providing food and fiber to feed, house, and clothe the world."**

Singh is still involved in developing new technologies as he continues to explore emerging tech and its application to farming and construction equipment as a John Deere Fellow.

Singh was the first in his family to go to college. He earned a bachelor's degree in electrical engineering in 1989 from the Madan Mohan Malaviya Engineering College, in Gorakhpur, India. (This institution became the Madan Mohan Malaviya University of Technology in 2013.) He went on to earn a master's degree in engineering in 1991 from the Indian Institute of Technology Roorkee, in Uttarakhand, and a Ph.D. in engineering in 1996 from the Indian Institute of Technology Delhi.

This was followed by postdoc positions working on various aspects of power electronics, including power-quality control, and AC-to-DC and DC-to-DC converters for use in telecommunications products. Singh spent about two years as a postdoc at ETS Montreal and then a year as a research fellow at Concordia University, also in Montreal.

In 2000, he became an assistant professor of electrical engineering and computer science at Tulane University, in New Orleans. There he was involved in R&D projects on power quality-control converters and renewable energy systems. He taught courses in power electronics, microelectromechanical systems, and RF engineering.

There are many career opportunities for engineers who want to work on power electronics, Singh says. That includes working on solar and wind power, electric vehicles, industrial power, and consumer electronics.

If you're interested in learning about how to convert gasoline-powered vehicles to electric ones, Singh suggests taking at least one course in power systems to understand how EV power systems work. Also consider taking a power-electronics course and learning about power topologies, which are the various ways that power components may be interconnected, he says. To design semiconductor devices that use new materials like SiC and GaN, learn some materials science.

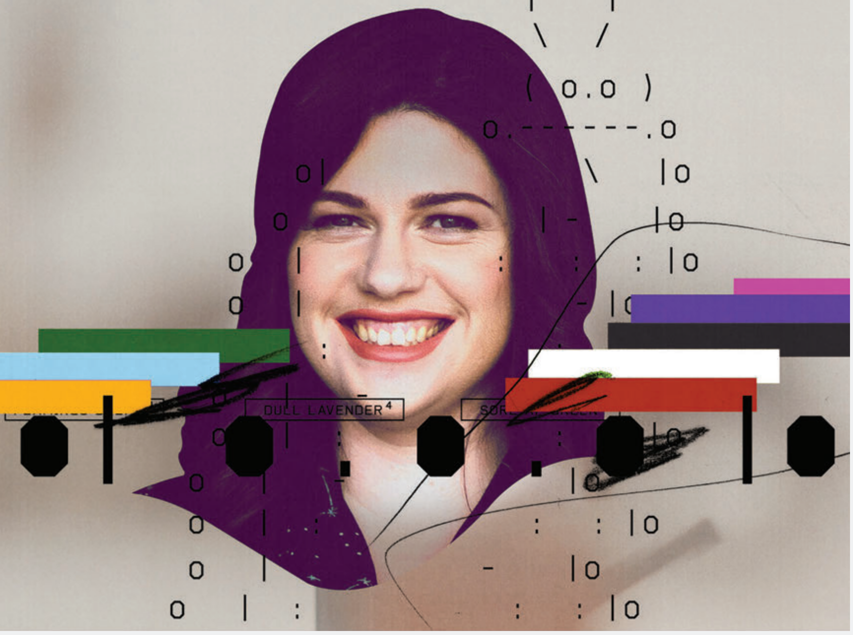
Does Singh get to test-drive the vehicles he's helping electrify? The answer is yes.

"It's incredibly rewarding to test-drive a machine that I've helped to develop," he says. "It's one thing to talk about how it will benefit customers, but it's a whole other thing to experience the machine the way our construction workers get to. It's one of the best aspects of my job." ■

Employer:
John Deere,
Fargo, N.D.

Title:
External relationships manager for Australia, Canada, New Zealand, and the United States

Education:
Bachelor's degree in electrical engineering, Mohan Malaviya Engineering College; master's degree in engineering, Indian Institute of Technology Roorkee; Ph.D. in engineering, Indian Institute of Technology Delhi



5 Questions for Janelle Shane

Why AI is so often weird, argumentative, and wrong

Long before most people began playing around with generative AI models like ChatGPT and DALL-E, Janelle Shane started documenting AI oddities. An optics researcher by training, she's also held a long fascination in testing AIs' ability to be, well, normal. With more and more people testing AI limits than ever before, Shane took a minute to answer five relatively normal questions from *IEEE Spectrum* about why chatbots love to talk back and why image-recognition models are head over heels for giraffes.

How has AIs' weirdness changed in the past year?
Janelle Shane: They've gotten less weird, more coherent. Instead of being absurd and half-incomprehensible, they've become way more fluent and more subtly wrong in ways that are harder to detect. But—they're a lot more accessible now. People have the chance to experiment with them themselves. So from that standpoint, the weirdness of these models is a lot more evident.

You've written that it's outrageous that chatbots like Google's Bard and Bing Chat are seen as an alternative to search engines. What's the problem?
Shane: The problem is how incorrect—and in many cases very subtly incorrect—these answers are, and you may not be able to tell at first, if it's outside your area of expertise. The problem is the answers do look vaguely correct. But [the chatbots] are making up papers, they're making up citations or getting facts and dates wrong, but presenting it the same way they present actual search results. I think people can get a false sense of confidence on what is really just probability-based text.

Janelle Shane's AI humor blog, AI Weirdness, and her book, You Look Like a Thing and I Love You: How AI Works, and Why It's Making the World a Weirder Place, *use cartoons and humorous pop-culture experiments to look inside the artificial intelligence algorithms that run our world.*

You've noted as well that chatbots are often confidently incorrect, and even double down when challenged. What do you think causes that?
Shane: They're trained on books and Internet dialogues and Web pages in which humans are generally very confident about their answers. Especially in the earliest releases of these chatbots, before the engineers did some tweaking, you would get chatbots that acted like they were in an Internet argument and doubling down sounding like they're getting very hyped up and emotional about how correct they are. I think that came straight from imitating humans in Internet arguments during training.

What inspired you to ask ChatGPT to draw things or create ASCII art?
Shane: I wanted to find ways in which it could be obvious at a glance that these models are making mistakes, and also what kinds of mistakes they're making. To understand how wrong they are about quantum physics, you have to know quantum physics well enough to know it's making things up. But if you see it generate a blob, claim it's a unicorn, and describe how skillfully it has generated this unicorn, you get an idea of just what kind of overconfidence you're dealing with.

Why is AI so obsessed with giraffes?
Shane: That's a meme going back to the early days of image-captioning AIs. The origin of the term "giraffing" was somebody who set up a Tumblr bot that automatically captioned images and started to notice that quite a lot of them had phantom giraffes in them.

It's kind of a fun example animal to use at this point. When I was talking with Visual Chatbot, one of these early question-and-answer image-describing bots, that's what I picked to test: What happens if you ask it how many giraffes there are? It would always give you a nonzero answer because people didn't tend to ask that question in training when the answer was zero. ■

Photo-illustration by Stuart Bradford

WIND-TO-HYDROGEN TECH GOES TO SEA

Is electrolysis cheaper offshore? A new project will find out

By Matthias Mueller & Roland Dittmeyer

ILLUSTRATIONS BY JOHN MACNEILL

IN A FUTURE WIND FARM, far out at sea, each individual wind turbine could have all the necessary systems to produce hydrogen on a platform affixed to the turbine's tower. Hydrogen from multiple turbines would be fed via pipeline to a Power-to-X platform [left] where the gas would be used to produce fuels such as methane or methanol.

Imagine this hopeful, and not impossible, energy scenario for the year 2040. Many countries have met their climate goals and are on track to be completely carbon neutral. Wind and solar parks produce a large portion of their energy. Then, as now, wind farms are operating off the world's coasts—but not all of these offshore sites are connected to the mainland via underwater power cables.

Some of the wind farms instead sit in clusters more than 100 kilometers out at sea. They are highly automated production islands that directly convert wind energy to hydrogen, with a few of them processing the gas into fuels and other goods. In these clusters, the wind turbines are integrated with electrolyzers that generate hydrogen from desalinated seawater. Chemical plants on dedicated platforms then process part of the hydrogen, combining it with nitrogen to make ammonia, or with carbon dioxide to produce substitutes for fossil fuels.

Ships regularly dock at these offshore platforms to deliver raw materials and take away the fuels and goods produced, but all the processes are fully automated and largely self-sufficient. Someday, even the ships themselves might be autonomous. Back on shore, service technicians support operations remotely and only have to head out to sea a few times a year to check on machinery and make adjustments.

It seems like science fiction now, but major efforts are already underway to demonstrate the technologies needed to realize this vision. Most of the activity is in Europe, where there are at least 10 major offshore wind and hydrogen projects, including demonstration systems being built or planned in the North Sea, the Atlantic, and off the coast of Ireland. In France, for example, the hydrogen producer Lhyfe is operating a pilot project called SEM-REV off the coast of Saint-Nazaire, which has been producing small amounts of hydrogen since September 2022.

A British company, ERM, plans to have a 10-megawatt demonstration project called Dolphyn up and running off the coast of Aberdeen, Scotland, in 2026. Sweden's Vattenfall is aiming to build an offshore, hydrogen-producing wind-turbine demonstrator in the same area. Denmark is planning a hydrogen island designed to generate about 1 million tonnes of offshore hydrogen starting in 2030. And the Norwegian company H2Carrier recently received approval in principle for its concept for an industrial-scale floating production unit to make green ammonia at sea.

Longer term, California, the Canadian province of Nova Scotia, Japan, and Western Australia are all looking to the sea to help meet their demands for hydrogen.

At Siemens Energy, we are working with a consortium of 32 partners from industry and academia on a wind-and-hydrogen project called H2Mare. Together, Siemens Energy and Siemens Gamesa are investing a total of €120 million in the technology. H2Mare began in 2021 and will run until 2025. By then, we expect to have tested a 5-MW offshore electrolysis system and a full process chain for fuel production at a scale of about 50 liters per day. We also expect to demonstrate the viability of other key concepts and systems, as well as the ability of these systems to interact with each other reliably in the harsh environment out at sea.

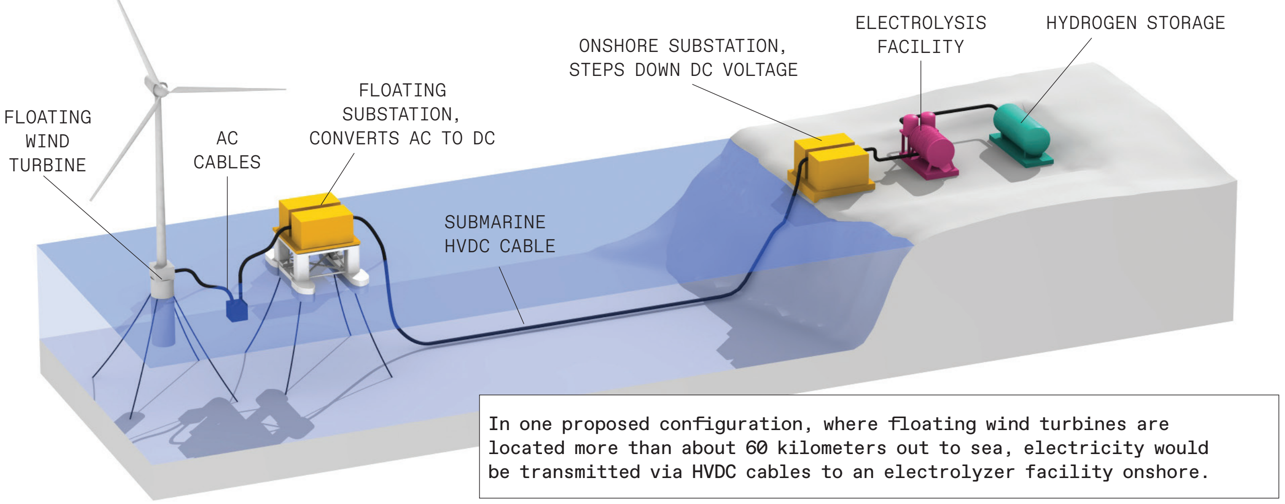
H2MARE IS ONE OF three hydrogen flagship projects that have received a total of €700 million in funding from the German Federal Ministry of Education and Research. And Germany isn't the only country investing in hydrogen technologies. Even a casual reading of the business press might convince you that the world has fallen in love with this molecule. The European Union has approved over €10 billion in funding for hydrogen-related industrial projects. The U.S. Department of Energy has spent over US $9 billion on developing a hydrogen economy, with many of its initiatives specified in the Inflation Reduction Act of 2022. In mid-2022, the International Renewable Energy Agency counted 32 countries that had adopted hydrogen strategies and 11 others that were preparing such plans.

Why all the hype about hydrogen? In the fight against climate change, many countries have pledged to reduce their CO_2 emissions to net zero. Unlike today, the future will see a climate-neutral world where energy will primarily be electricity from photovoltaics, wind turbines, renewable resources, and probably some nuclear. But not all of the vehicles, buildings, and industrial processes that now use fossil fuels can run on electricity

US $5 PER KILOGRAM

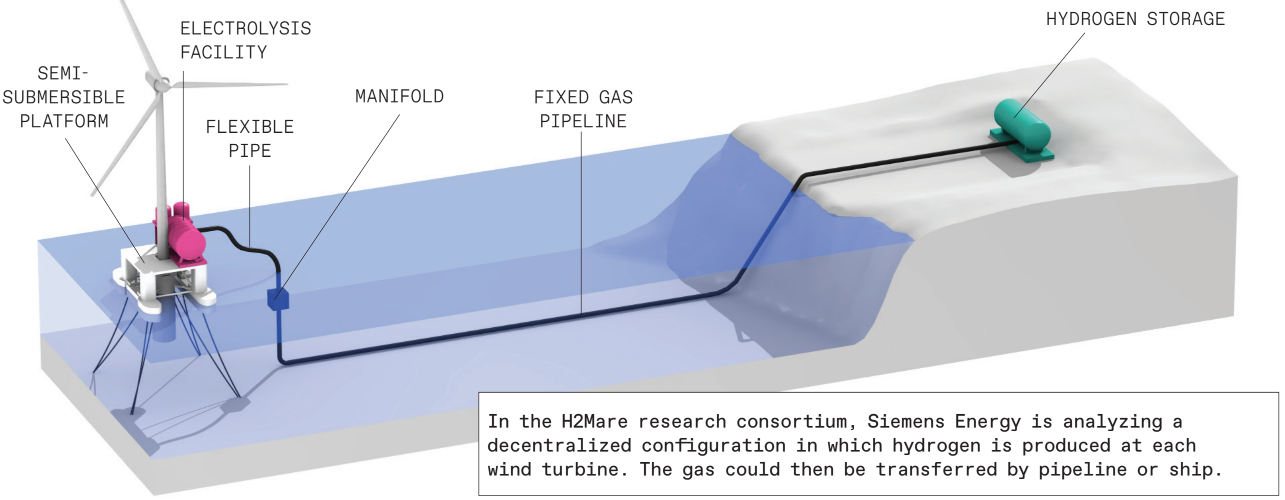
Cost of green hydrogen today. Conventional, or gray, hydrogen: $1.50 to $2.00

ELECTROLYSIS PERFORMED ONSHORE



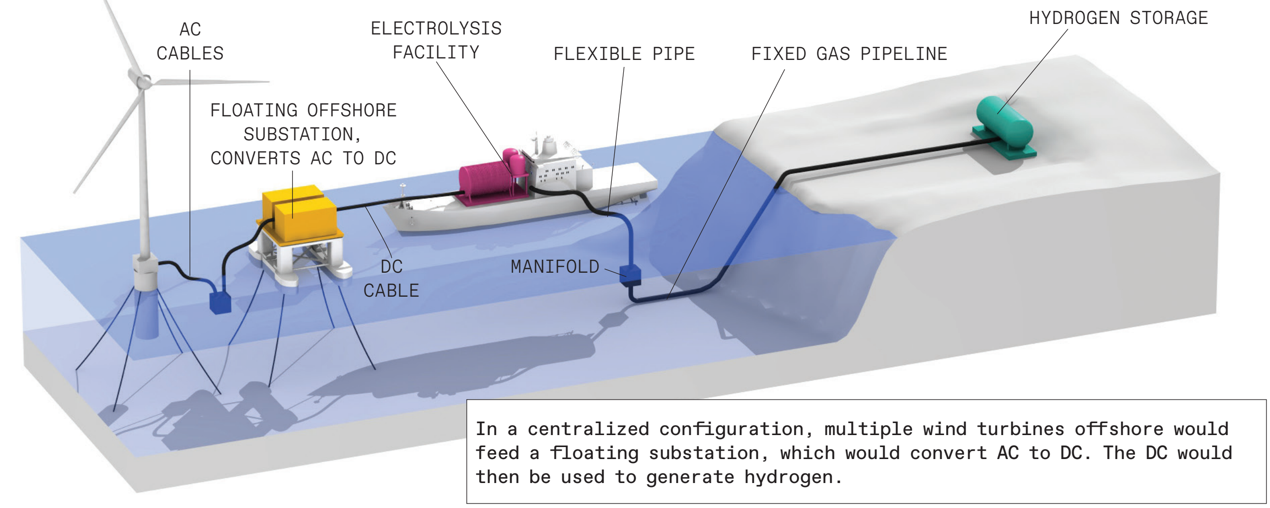
In one proposed configuration, where floating wind turbines are located more than about 60 kilometers out to sea, electricity would be transmitted via HVDC cables to an electrolyzer facility onshore.

ELECTROLYSIS PERFORMED OFFSHORE, ON THE WIND-TURBINE PLATFORM



In the H2Mare research consortium, Siemens Energy is analyzing a decentralized configuration in which hydrogen is produced at each wind turbine. The gas could then be transferred by pipeline or ship.

ELECTROLYSIS PERFORMED OFFSHORE, ON A FLOATING PLATFORM



In a centralized configuration, multiple wind turbines offshore would feed a floating substation, which would convert AC to DC. The DC would then be used to generate hydrogen.

SOURCE: "DEDICATED LARGE-SCALE FLOATING OFFSHORE WIND TO HYDROGEN: ASSESSING DESIGN VARIABLES IN PROPOSED TOPOLOGIES," RENEWABLE AND SUSTAINABLE ENERGY REVIEWS, 1 MARCH 2022 alone. Airplanes, for example, won't be able to fly long distances on battery power. In addition, for many uses, energy can't be used the instant it's generated but must be stored for hours or days and transferred across continents or even oceans, neither of which is currently economically or technologically feasible.

The European Union's net-zero scenario for 2050 already calls for an installed offshore wind capacity of about 450 gigawatts for power generation.

The upshot is that a portion of the green electricity will have to be converted to other types of energy appropriate for specific applications. Experts call this Power-to-X (PtX). These applications tend to be strongly clustered in three broad sectors: transportation, heating, and industry, in such segments as manufacturing and processing. All are quite energy intensive. Powering these applications will require electrifying these sectors or converting electricity to a more suitable form via PtX.

That's where hydrogen comes into play. The technology to produce hydrogen by electrolyzing water has been around for more than 200 years. The gas can power fuel-cell vehicles or gas turbines; it can be used directly in chemical processes or converted with CO_2 to produce methane, methanol, and other substitutes for fossil fuels. If the electricity used to produce the hydrogen and the fuels derived from it comes from renewable sources, these products are considered "green."

Hydrogen is thus greasing the wheels of the global transition to cleaner energy. And the world is going to need a lot more of it. In 2021, global hydrogen demand was 94 million tonnes, most of it used in refining and in chemical industries. Almost all hydrogen produced today is designated as brown, black, or gray, meaning it was generated by burning natural gas or coal. The process emits about 10 tonnes of CO_2 per tonne of hydrogen. In the future we'll need to replace this dirty hydrogen with green hydrogen, produced by electrolysis using renewable electricity.

Depending on how rapidly countries decarbonize, the International Energy Agency predicts that global demand for hydrogen will reach 115 million to 130 million tonnes per year in 2030, about 30 million of which will come from low-emission production. However, much more than that will be needed for the world to achieve net-zero emissions by 2050. The IEA calculates this amount to be around 200 million tonnes of hydrogen in 2030, half of which would come from low-emission production. There's still a long way to go: According to the IEA, not even 1 percent of hydrogen produced in 2021, amounting to 0.6 million tonnes, was low emission.

30 MILLION TONNES

Amount of low-emission hydrogen the IEA predicts will be produced in 2030

0.6 MILLION TONNES

Amount made In 2021

HOW WILL OFFSHORE HYDROGEN generation fit into existing decarbonization plans? The European Union's net-zero scenario for 2050 already calls for an installed offshore wind capacity of about 450 gigawatts for power generation. (Today, a typical offshore wind farm has about 1 GW of installed capacity; future farms will offer about 2 GW each.) Recent analysis, however, has suggested that the EU could install, for hydrogen production, a great deal more offshore wind generation beyond the 450 GW specified in the net-zero projections—perhaps hundreds of gigawatts more, in fact.

To meet such targets, it'll be necessary to build, and build fast. Green hydrogen production requires electrolyzers, solar and wind parks, and clean water—about 10 liters per kilogram of hydrogen generated. Add to this the PtX systems to produce methane, methanol, synthetic e-fuels, and ammonia. For these green products to be competitive, the sites will have to offer low power-generation costs and will have to produce power at near-full capacity much of the time.

Offshore wind parks can meet both of these criteria. Offshore sites could make it possible for densely populated regions like Europe and Japan to generate at least part of their hydrogen close to coastal demand centers, thereby cutting transportation costs. Also, wind speeds are generally higher and steadier out at sea, permitting consistently greater output.

The savings would accrue from several factors. In a typical scenario, wind power out at sea would be converted only once to direct current and then used to electrolyze water. The water supply would literally surround the offshore platform—all that would be needed would be to desalinate and purify it. In contrast, electricity produced by offshore wind power typically requires multiple conversions and transmission across long distances before it's fed into the grid or an electrolyzer onshore, processes that siphon off power and reduce efficiency. Delivery of hydrogen from offshore, on the other hand, would be easy via pipeline. PtX products such as methanol and ammonia would be even easier to transport than hydrogen, whether via pipeline or ship.

OUR H2MARE PROJECT has several major goals. We are doing the detailed analysis necessary to determine conclusively whether it will make economic sense, and be technically feasible, to produce hydrogen and other fuels offshore. And if so, how, exactly? What would be the best configurations, distances, production volumes, and so on? Although we're not going to build a full-scale offshore PtX production platform, we do plan to build a test platform on a barge on the open sea, as well as an onshore test setup of the electrolysis system.

One of the most important questions we'll be answering is, What is the best way to supply PtX production facilities out at sea? To produce fuels or goods such as ammonia, these facilities can be supplied with either hydrogen or with electricity; in the latter case, the PtX platform would produce its own hydrogen from electrolysis of desalinated seawater.

But if the PtX facility is being furnished with hydrogen from other platforms, the question becomes, What is the best way to produce the gas? You could produce hydrogen at each wind turbine and then combine it at the PtX facility, or you could combine the electricity from multiple wind turbines to produce hydrogen on a separate platform and then supply it to the PtX platform. It turns out that the former option is better.

Another big question is how to achieve stable production for these multimegawatt wind-hydrogen islands as well as autonomous operation of the PtX islands. Regardless of whether hydrogen or PtX products are being generated, the production islands won't be directly connected to an onshore power grid, and so they'll need to operate reliably on their own.

That won't be easy, given the extremely dynamic environment these platforms will have to function in. Offshore, the weather alternates among brisk winds, storms, and occasional lulls, sometimes going from one to another in mere minutes. That will mean great variability in the levels of power supplied by the wind turbines. As a result, the supply of electricity and hydrogen to the various facilities will vary widely.

That variability will also strain the electrical systems. Because there's no grid connection, the platforms will basically operate as small, isolated power grids and therefore have to handle any sudden surges in power.

Conversely, after a long lull in the wind, the chemical plants and other offshore facilities will have to restart themselves without receiving external power. This is called black-start capability. There are no standard procedures for doing this in a tiny, automated, and isolated grid, so we are trying to devise some. We're considering, for example, what kinds of batteries to use and how to design chemical processes so that the facilities can restart themselves reliably.

The electrolyzers, too, must be chosen for best performance in the dynamic environment out at sea. There are three main types of industrial electrolysis, and of the three, the proton-exchange-membrane (PEM) is ideal in this scenario. A PEM electrolyzer starts up within minutes and can handle rapid load changes. As part of H2Mare, we are designing and building PEM cells specifically for offshore use, and we expect to test them soon to see how well they perform when the power is highly variable.

What we're finding is that process control will play an important role. The individual electrolyzers connected to a turbine will need to be controlled in such a way that they age uniformly and their total downtime is kept to a minimum. Our experiments now are aimed at finding the most efficient operating mode. For example, there's an investigation into whether the electrolyzer's waste heat can be used for desalination, and if this amount of heat is sufficient over the entire operating range of the plant.

H2MARE PROJECT

Project goal: Investigate offshore production of hydrogen and secondary products

Funding: Partially funded by the German Federal Ministry of Education and Research

Duration: April 2021 to March 2025

Consortium: 32 partners from industry and research

Project budget: Approximately €150 million, about €100 million of which consists of subsidies

H2Mare will also look into initial strategies for managing a small island grid. What happens when an electrolyzer shuts down unexpectedly? Where can the excess electrical energy be channeled at a speed fast enough to prevent the grid from collapsing? And conversely, How can the electrolyzer be designed to handle a situation where the wind fades away and the power supply is suddenly gone?

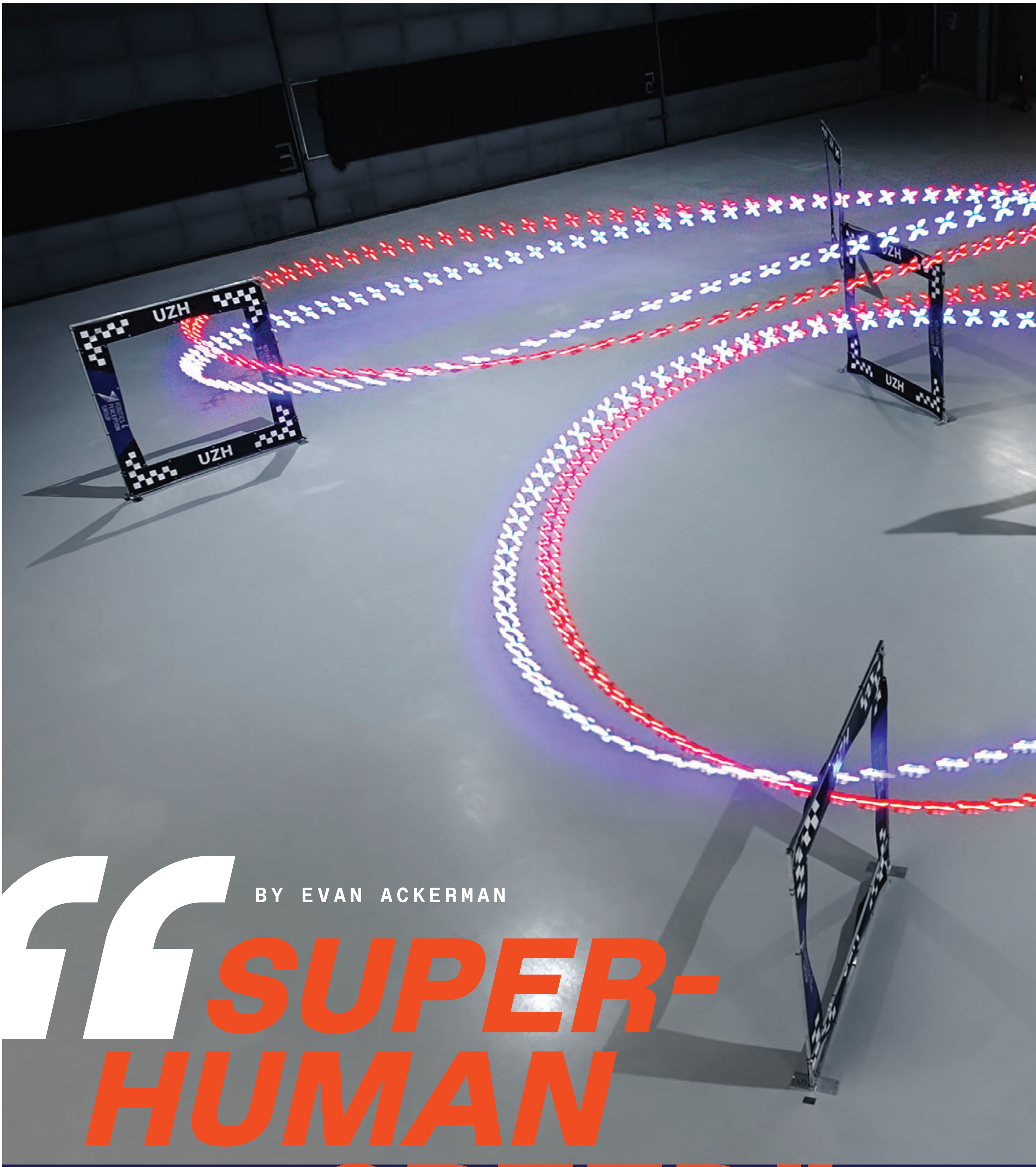
To answer these questions, we intend to build and operate, in the next two years, a 5-MW electrolyzer with a seawater desalinization system in an onshore test. For the tests, we'll re-create an offshore environment, including offshore-wind profiles.

FOR THE POWER GENERATION and electrolysis systems, as well as the PtX facilities, the most important research objective is figuring out how to operate stably despite the dynamic environment, isolation, and automation. The chemical processes are generally most efficient when there's a constant supply of power and reactants. But out at sea, they will inevitably fluctuate, so we're developing concepts that use batteries or hydrogen-storage systems to smooth out the fluctuations. The trick will be to keep the cost of these buffers to a minimum. Another possibility is a modular design in which parallel modules are started up or shut down in coordination with one another.

The home base for much of our PtX-focused research is the Energy Lab 2.0 at Karlsruhe Institute of Technology. The lab has a variety of energy-related R&D facilities, including ones for renewable-energy generation, energy storage, and PtX, as well as smart-home and electric-vehicle infrastructure. For H2Mare, it serves as a kind of dry dock: There, we are operating the prototype PtX plants with power profiles typical for offshore wind farms and are simulating their optimal operation under transient conditions and in island mode.

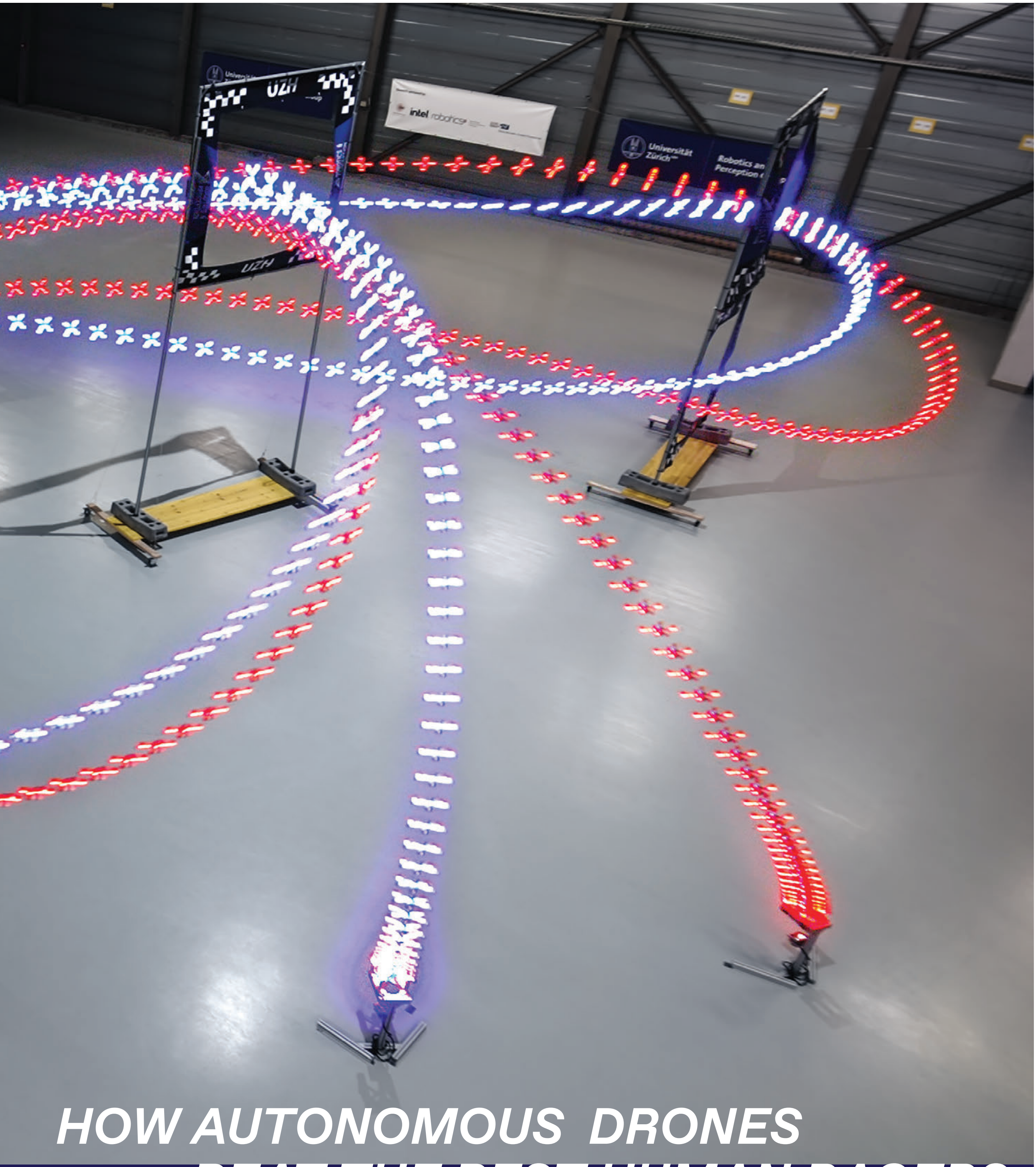
Meanwhile, Siemens Energy is going ahead with plans to develop a commercial electrolysis system for offshore wind turbines. According to current estimates, the company's first prototype of a wind turbine with integrated hydrogen production could be in the water in 2026, and commercial projects with capacities ranging from several hundred megawatts to gigawatt scale could follow by the end of the 2020s.

If it all goes well, offshore hydrogen could help enable the kind of rapid, mass-scale transition to climate-neutral energy that we'll need to meet the goals for the 2040 time frame. We expect that self-sufficient commercial-scale PtX-production islands will be a realistic possibility, but not until 2040 at the earliest. Whether they'll look and function exactly like those we've described in this article will depend in large measure on knowledge gained from H2Mare and from similar projects in Europe and elsewhere. ■



BY EVAN ACKERMAN

“SUPER-HUMAN SPEED”



HOW AUTONOMOUS DRONES BEAT THE BEST HUMAN RACERS

The competition course was designed by a professional drone pilot and contains seven gates in a volume of 30 by 30 by 8 meters. The arrangement of the gates requires the drones to carry out complex acrobatic maneuvers, where Swift [blue], the autonomous-drone system, has a much tighter line than the human-piloted drone [red], as shown in this time-lapse image. LEONARD BAUERSFELD

The drone screams.

It's flying so fast that following it with my camera is hopeless, so I give up and watch in disbelief. The shrieking whine from the four motors of the racing quadrotor Dopplers up and down as the drone twists, turns, and backflips its way through the square plastic gates of the course at a speed that is literally superhuman. I'm cowering behind a safety net, inside a hangar at an airfield just outside of Zurich, along with the drone's creators from the Robotics and Perception Group at the University of Zurich.

"I don't even know what I just watched," says Alex Vanover, as the drone comes to a hovering halt after completing the 75-meter course in 5.3 seconds. "That was beautiful," Thomas Bitmatta adds. "One day, my dream is to be able to achieve that." Vanover and Bitmatta are arguably the world's best drone-racing pilots, multiyear champions of highly competitive international drone-racing circuits. And they're here to prove that human pilots have not been bested by robots. Yet.

Comparing these high-performance quadrotors to the kind of drones that hobbyists use for photography is like comparing a jet fighter to a light aircraft: Racing quadrotors are heavily optimized for speed and agility. A typical racing quadrotor can output 35 newtons of thrust, with four motors spinning tribladed propellers at 30,000 rpm. The drone weighs just 870 grams, including a camera system and a 1,800-milliampere-hour battery that lasts a mere 2 minutes. This extreme power-to-weight ratio allows the drone to accelerate at 4.5 *g*'s, reaching 100 kilometers per hour in less than a second.

The autonomous racing quadrotors have similar specs, but the one we just saw fly doesn't have a camera, because it doesn't need one. Instead, the hangar has been equipped with a 36-camera infrared tracking system that can localize the drone within millimeters, 400 times every second. By combining the location data with a map of the course, an off-board computer can steer the drone along an optimal trajectory, which would be difficult, if not impossible, for even the best human pilot to match.

These autonomous drones are, in a sense, cheating. The human pilots have access to the single view only from a camera mounted on the drone, along

with their knowledge of the course and flying experience. So, it's really no surprise that US $400,000 worth of sensors and computers can outperform a human pilot. But the reason why these professional drone pilots came to Zurich is to see how they would do in a competition that's actually fair.

SOLVING DRONE RACING

"We're trying to make history," says Davide Scaramuzza, who leads the Robotics and Perception Group at the University of Zurich (UZH). "We want to demonstrate that an AI-powered, vision-based drone can achieve human-level, and maybe even superhuman-level, performance in a drone race." Using vision is the key here: Scaramuzza has been working on drones that sense the way most people do, relying on onboard cameras to perceive the world around them and making decisions based primarily on that visual data. This is what will make the race fair—human eyes and a human brain versus robotic eyes and a robotic brain, each competitor flying the same racing quadrotors as fast as possible around the same course.

"Drone racing [against humans] is an ideal framework for evaluating the progress of autonomous vision-based robotics," Scaramuzza explains. "And when you solve drone racing, the applications go much further because this problem can be generalized to other robotics applications, like inspection, delivery, or search and rescue."

While there are already drones doing these tasks, they tend to fly slowly and carefully. According to Scaramuzza, being able to fly faster can make drones more efficient, improving their flight duration and range and thus their utility. "If you want drones to replace humans at dull, difficult, or dangerous tasks, the drones will have to do things faster or more efficiently than humans. That is what we are working toward—that's our ambition," Scaramuzza explains. "There are many hard challenges in robotics. Fast, agile, autonomous flight is one of them."

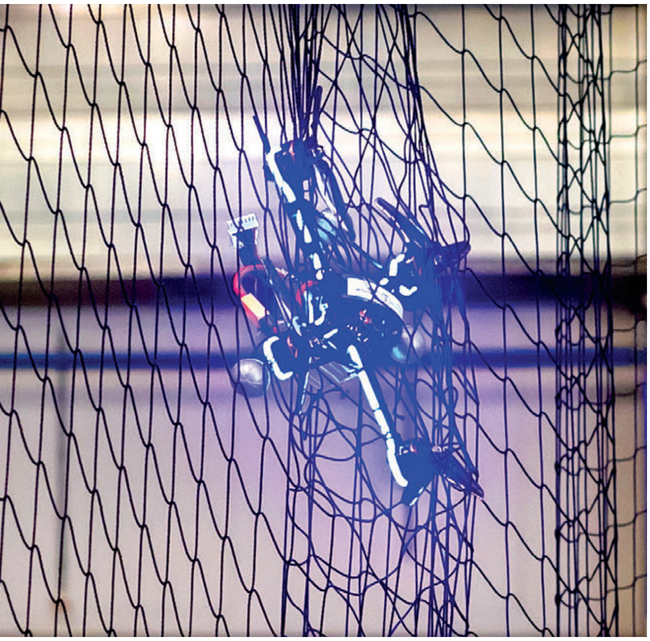
AUTONOMOUS NAVIGATION

Scaramuzza's autonomous-drone system, called Swift, starts with a three-dimensional map of the course. The human pilots have access to this map

A human-piloted red racing drone chases an autonomous vision-based blue drone [left] through a gate at over 13 meters per second.

The human-piloted drones [red] are each equipped with a first-person-view (FPV) camera; each of the autonomous drones [blue] has an Intel RealSense vision system powered by a Nvidia Jetson TX2 onboard computer. Both sets of drones are equipped with reflective markers that are tracked by an external camera system for trajectory analysis.

TOP: LEONARD BAUERSFELD; BOTTOM: EVAN ACKERMAN (2)



Although the autonomous vision-based drones are fast, they are also less robust. Even small errors can lead to crashes from which the autonomous drones cannot recover.

LEFT: REGINA SABLOTNY; RIGHT: EVAN ACKERMAN

as well, so that they can practice in simulation. The goal of both human and robot-drone pilots is to fly through each gate as quickly as possible, and the best way of doing this is via what's called a time-optimal trajectory.

Robots have an advantage here because it's possible (in simulation) to calculate this trajectory for a given course in a way that is provably optimal. But knowing the optimal trajectory gets you only so far. Scaramuzza explains that simulations are never completely accurate, and things that are especially hard to model—including the turbulent aerodynamics of a drone flying through a gate and the flexibility of the drone itself—make it difficult to stick to that optimal trajectory.

The solution, says Scaramuzza, is to use deep reinforcement learning. You're still training your system in simulation, but you're also giving your reinforcement-learning algorithm the task of making continuous adjustments, tuning the system to a specific track in a real-world environment. Some real-world data is collected on the track and added to the simulation, allowing the algorithm to incorporate realistically "noisy" data to better prepare it for flying the actual course. The drone will never fly the most mathematically optimal trajectory this way, but it will fly much faster than it would using a trajectory designed in an entirely simulated environment.

From there, the only thing that remains is to determine how far to push Swift. One of the lead researchers, Elia Kaufmann, quotes Mario Andretti: "If everything seems under control, you're just not going fast enough." Finding that edge of control is the only way the autonomous vision-based quadrotors will be able to fly faster than those controlled by humans. "If we had a successful run, we just cranked up the speed again," Kaufmann says. "And we'd keep doing that until we crashed. Very often, our conditions for going home at the end of the day are either everything has worked, which never happens, or that all the drones are broken."

HOW THE ROBOTS FLY

Once Swift has determined its desired trajectory, it needs to navigate the drone along that trajectory. Whether you're flying a drone or driving a car, navigation involves two fundamental things: knowing where you are and knowing how to get where you want to go. The autonomous drones have calculated the time-optimal route in advance, but to fly that route, they need a reliable way to determine their own location as well as their velocity and orientation.

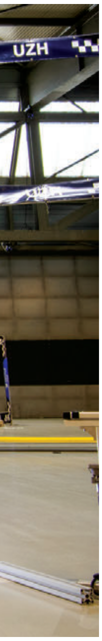
To that end, the quadrotor uses an Intel RealSense vision system to identify the corners of the racing gates and other visual features to localize itself on the course. A Nvidia Jetson TX2 module, which includes a GPU, a CPU, and associated hardware, manages all of the image processing and control on board.

Using only vision imposes significant constraints on how the drone flies. For example, while quadrotors are equally capable of flying in any direction, Swift's camera needs to point forward most of the time. There's also the issue of motion blur, which occurs when the exposure length of a single frame in the drone's camera feed is long enough that the drone's own motion over that time becomes significant. Motion blur is especially problematic when the drone is turning: The high angular velocity results in blurring that essentially renders the drone blind. The roboticists have to plan their flight paths to minimize motion blur, finding a compromise between a time-optimal flight path and one that the drone can fly without crashing.

HOW THE HUMANS FLY

For the human pilots, the challenges are similar. The quadrotors are capable of far better performance than pilots normally take advantage of. Pilot Thomas Bitmatta estimates that he flies his drone at about 60 percent of its maximum performance. But the biggest limiting factor for the human pilots is the video feed.

People race drones in what's called first-person view (FPV), using video goggles that display a real-time feed from a camera mounted on the front of the



Davide Scaramuzza [far left], Elia Kaufmann [far right], and other roboticists from the University of Zurich watch a close race.

drone. The FPV video systems that the pilots used in Zurich can transmit at 60 interlaced frames per second in relatively poor analog VGA quality. In simulation, drone pilots practice in HD at over 200 frames per second, which makes a substantial difference. "Some of the decisions that we make are based on just four frames of data," explains Bitmatta. "Higher-quality video, with better frame rates and lower latency, would give us a lot more data to use." Still, one of the things that impresses the roboticists the most is just how well people can fly with the video quality available. It suggests that these pilots develop the ability to perform the equivalent of the robot's localization and state-estimation algorithms.

It seems as though the human pilots are also attempting to calculate a time-optimal trajectory, Scaramuzza says. "Some pilots have told us that they try to visualize an imaginary line through a course, after several hours of rehearsal. So we speculate that they are actually building a mental map of the environment, and learning to compute an optimal trajectory to follow. It's very interesting—it seems that both the humans and the machines are reasoning in the same way."

BY THE NUMBERS: AUTONOMOUS RACING DRONES

Frame size:
23 centimeters

Weight: 870 grams

Maximum thrust:
35 newtons

Flight duration:
2 minutes

Acceleration:
4.5 *g*'s

Top speed:
100+ kilometers per hour

Onboard sensing:
Intel RealSense T265 tracking camera

Onboard computing:
Nvidia Jetson TX2

But in his effort to fly faster, Bitmatta tries to avoid following a predefined trajectory. "With predictive flying, I'm trying to fly to the plan that I have in my head. With reactive flying, I'm looking at what's in front of me and constantly reacting to my environment." Predictive flying can be fast in a controlled environment, but if anything unpredictable happens, or if Bitmatta has even a brief lapse in concentration, the drone will have traveled tens of meters before he can react. "Flying reactively from the start can help you to recover from the unexpected," he says.

WILL HUMANS HAVE AN EDGE?

"Human pilots are much more able to generalize, to make decisions on the fly, and to learn from experiences than are the autonomous systems that we currently have," explains Christian Pfeiffer, a neuroscientist turned roboticist at UZH who studies how human drone pilots do what they do. "Humans have adapted to plan into the future; robots don't have that long-term vision. I see that as one of the main differences between humans and autonomous systems right now."

Scaramuzza agrees. "Humans have much more experience, accumulated through years of interacting with the world," he says. "Their knowledge is so much broader because they've been trained across many different situations. At the moment, the problem that we face in the robotics community is that we always need to train an algorithm for each specific task. Humans are still better than any machine because humans can make better decisions in very complex situations and in the presence of imperfect data."

This understanding that humans are still far better generalists has placed some significant constraints on the race. The "fairness" is heavily biased in favor of the robots, in that the race, while designed to be as equal as possible, is taking place in the only environment in which Swift is likely to have a chance. The roboticists have done their best to minimize unpredictability—there's no wind inside of the hangar, for example, and the illumination is tightly controlled. "We are using state-of-the-art perception algorithms," Scaramuzza explains, "but even the best algorithms still have a lot of failure modes because of illumination changes."

REGINA SABLOTNY

To ensure consistent lighting, almost all of the data for Swift’s training was collected at night, says Kaufmann. “The nice thing about night is that you can control the illumination; you can switch on the lights and you have the same conditions every time. If you fly in the morning, when the sunlight is entering the hangar, all that backlight makes it difficult for the camera to see the gates. We can handle these conditions, but we have to fly at slower speeds. When we push the system to its absolute limits, we sacrifice robustness.”

> **“I THINK THERE’S A LOT THAT WE AS HUMANS CAN LEARN FROM HOW THESE ROBOTS FLY.”**
> —THOMAS BITMATTA

RACE DAY

The race starts on a Saturday morning. Sunlight streams through the hangar’s skylights and open doors, and as the human pilots and autonomous drones start to fly test laps around the track, it’s immediately obvious that the vision-based drones are not performing as well as they did the night before. They’re regularly clipping the sides of the gates and spinning out of control, a telltale sign that the vision-based state estimation is being thrown off. The roboticists seem frustrated. The human pilots seem cautiously optimistic.

The winner of the competition will fly the three fastest consecutive laps without crashing. The humans and the robots pursue that goal in essentially the same way, by adjusting the parameters of their flight to find the point at which they’re barely in control. Quadrotors tumble into gates, walls, floors, and ceilings, as the racers push their limits. This is a normal part of drone racing, and there are dozens of replacement drones and staff to fix them when they break.

There will be several different metrics by which to decide whether the humans or the robots are faster. The external localization system used to actively control the autonomous drone last night is being used today for passive tracking, recording times for each segment of the course, each lap of the course, and for each three-lap multidrone race.

As the human pilots get comfortable with the course, their lap times decrease. Ten seconds per lap. Then 8 seconds. Then 6.5 seconds. Hidden behind their FPV headsets, the pilots are concentrating intensely as their shrieking quadrotors whirl through the gates. Swift, meanwhile, is consistently clocking lap times below 6 seconds but is frequently unable to complete three consecutive laps without crashing. Seeing Swift’s lap times, the human pilots push themselves, and their lap times decrease further. It’s going to be very close.

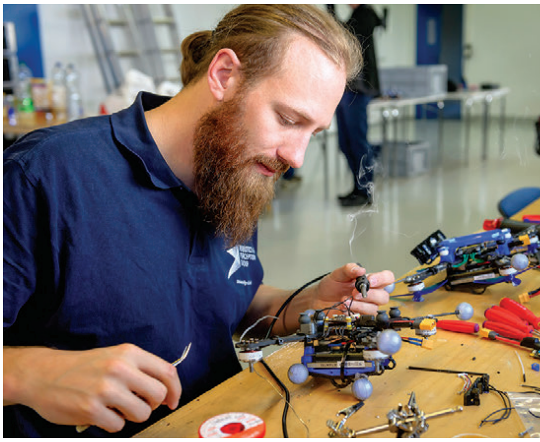
The head-to-head races start, with Swift and a human pilot launching side-by-side at the sound of the starting horn. The human is immediately at a disadvantage, because a person’s reaction time is slow compared to that of a robot: Swift can launch in less than 100 milliseconds, while a human takes about 220 ms to hear a noise and react to it.

On the course, the human pilots can *almost* keep up with Swift: The robot’s best three-lap time is 17.465 seconds, while Bitmatta’s is 18.746 seconds and Vanover manages 17.956 seconds. But in nine head-to-head races with Swift, Vanover wins four, and in seven races, Bitmatta wins three. That’s because Swift doesn’t finish the majority of the time, colliding either with a gate or with its opponent. The human pilots can recover from collisions, even relaunching from the ground if necessary. Swift doesn’t have those skills. The robot *is* faster, but it’s also less robust.

BOTTOM: EVAN ACKERMAN (2)

Thomas Bitmatta [left] examines flight paths recorded by the external tracking system. The human pilots felt they could learn to fly better by studying the robots.

UZH’s Elia Kaufmann [right] prepares an autonomous vision-based drone for a race. Since landing gear would only slow racing drones down, they take off from stands, which allow them to launch directly toward the first gate.



Bitmatta [left], a two-time MultiGP International Open World Cup champion, pilots his drone through the course in FPV. Both the Swift system and the human pilots crashed dozens of drones, which were constantly being repaired [above].

TOP: REGINA SABLOTNY (2)

GETTING EVEN FASTER

“The absolute performance of the robot—when it’s working, it’s brilliant,” says Bitmatta, when I speak to him at the end of race day. “It’s a little further ahead of us than I thought it would be. It’s still achievable for humans to match it, but the good thing for us at the moment is that it doesn’t look like it’s very adaptable.”

UZH’s Kaufmann doesn’t disagree. “Before the race, we had assumed that consistency was going to be our strength. It turned out not to be.” Making the drone more robust so that it can adapt to different lighting conditions, Kaufmann adds, is mostly a matter of collecting more data. “We can address this by retraining the perception system, and I’m sure we can substantially improve.”

Kaufmann believes that under controlled conditions, the potential performance of the autonomous vision-based drones is already well beyond what the human pilots are capable of. Even if this wasn’t conclusively proved through the competition, bringing the human pilots to Zurich and collecting data about how they fly made Kaufmann even more confident in what Swift can do. “We had overestimated the human pilots,” he says. “We were measuring their performance as they were training, and we slowed down a bit to increase our success rate, because we had seen that we could fly slower and still win. Our fastest strategies accelerate the quadrotor at 4.5 *g*’s, but we saw that if we accelerate at only 3.8 *g*’s, we can still achieve a safe win.”

Bitmatta feels that the humans have a lot more potential, too. “The kind of flying we were doing last year was nothing compared with what we’re doing now. Our rate of progress is really fast. And I think there’s a lot that we as humans can learn from how these robots fly.”

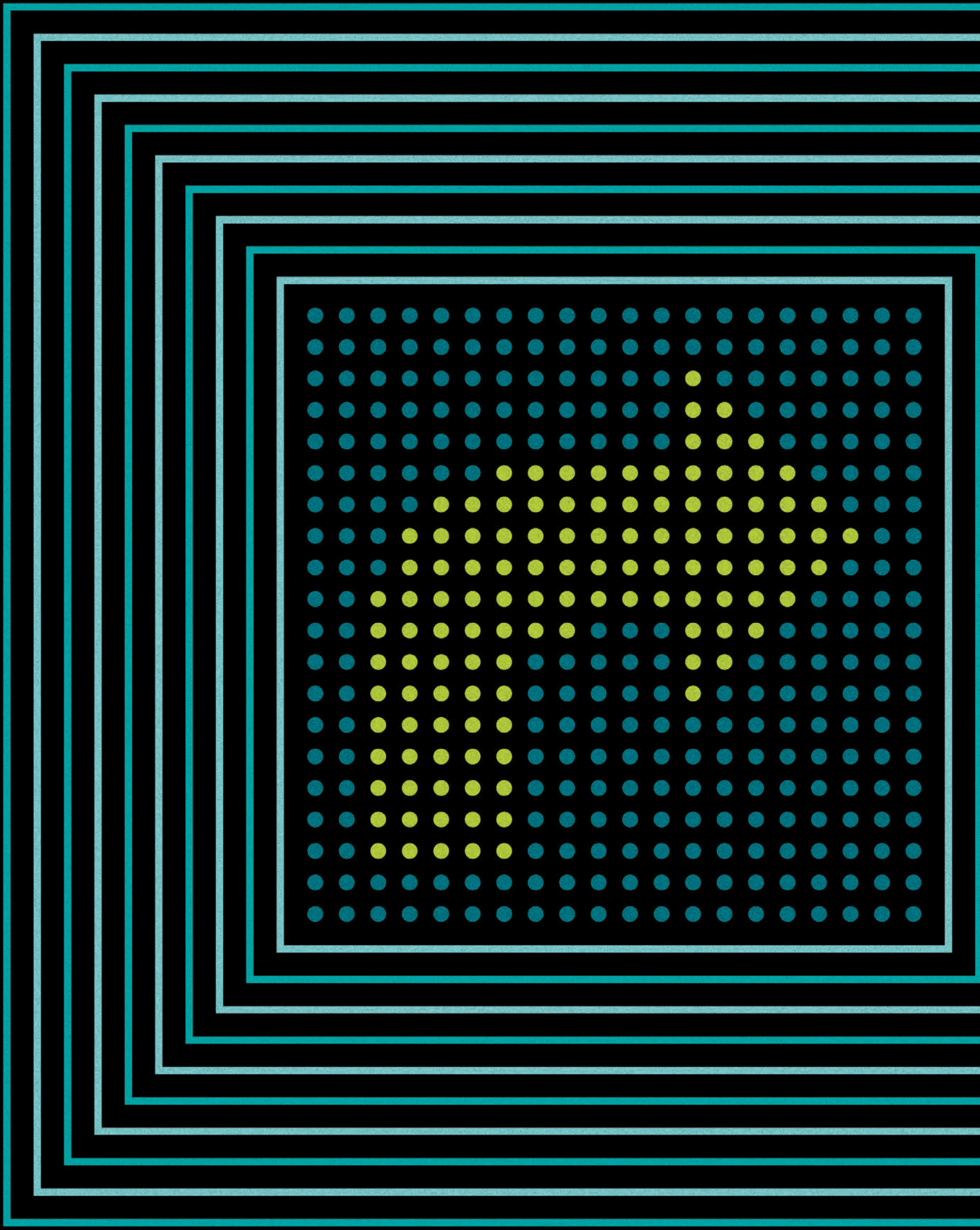
USEFUL FLYING ROBOTS

As far as Davide Scaramuzza is aware, the event in Zurich, which was held last summer, was the first time that a fully autonomous mobile robot achieved world-champion performance in a real-world competitive sport. But, he points out, “this is still a research experiment. It’s not a product. We are very far from making something that can work in any environment and any condition.”

Besides making the drones more adaptable to different lighting conditions, the roboticists are teaching Swift to generalize from a known course to a new one, as humans do, and to safely fly around other drones. All of these skills are transferable and will eventually lead to practical applications. “Drone racing is pushing an autonomous system to its absolute limits,” roboticist Christian Pfeiffer says. “It’s not the ultimate goal—it’s a stepping-stone toward building better and more capable autonomous robots.” When one of those robots flies through your window and drops off a package on your coffee table before zipping right out again, these researchers will have earned your thanks.

Scaramuzza is confident that his drones will one day be the champions of the air—not just inside a carefully controlled hangar in Zurich but wherever they can be useful to humanity. “I think ultimately, a machine will be better than any human pilot, especially when consistency and precision are important,” he says. “I don’t think this is controversial. The question is, when? I don’t think it will happen in the next few decades. At the moment, humans are much better with bad data. But this is just a perception problem, and computer vision is making giant steps forward. Eventually, robotics won’t just catch up with humans, it will outperform them.”

Meanwhile, the human pilots are taking this in stride. “Seeing people use racing as a way of learning—I appreciate that,” Thomas Bitmatta says. “Part of me is a racer who doesn’t want anything to be faster than I am. And part of me is really excited for where this technology can lead. The possibilities are endless, and this is the start of something that could change the whole world.” ■



LIDAR ON A CHIP ENTERS THE FAST LANE

Sensors for self-driving cars and robots will be tiny, reliable, and affordable

BY MICHAEL R. WATTS, CHRISTOPHER POULTON, MATTHEW BYRD & GREG SMOLKA Illustration by Greg Mably

AUTO ACCIDENTS ARE RESPONSIBLE for 1.3 million deaths annually, according to the World Health Organization. That's like losing the city of Prague each year. A switch to self-driving cars and trucks with various types of electronic sensors and sophisticated computers at the helm could save countless lives. But getting this promising technology into people's hands has been difficult, despite massive research investments and considerable technical progress. ● So when will self-driving cars really come to a driveway near you? The answer depends in part on whether such cars require a type of sensor called lidar, short for "light detection and ranging." Most groups developing autonomous vehicles see lidar as a critical part of the sensor suite required for safe operation, because it allows a detailed 3D map of the vehicle's environment to be constructed with much more fidelity than can be done with cameras.

Elon Musk, though, has been pushing Tesla to adopt a controversial cameras-only approach to autonomous driving. "Humans drive with eyes & biological neural nets, so makes sense that cameras & silicon neural nets are only way to achieve generalized solution to self-driving," Musk tweeted in 2021. The mechanical complexity and high cost of most lidar sensors—which not long ago would have added tens of thousands of dollars to the price of each vehicle—no doubt helped shape Musk's views. As early as 2016, he declared that "all Tesla vehicles exiting the factory have hardware necessary for Level 5 autonomy"—meaning that cars with cameras and computers alone have what's needed for fully autonomous driving.

Seven years and many crashes later, Tesla has not progressed past Level 2 autonomy, and traffic-safety specialists are questioning Musk's rejection of lidar. Requiring pricey sensors, though, would slow the widespread rollout of both advanced driver-assistance systems and fully autonomous driving. But reducing the cost of these sensors to a level that would satisfy automakers has remained an elusive goal for lidar manufacturers, which must also consider how to add their devices to cars without detracting from vehicle aesthetics.

We and others at our company, Analog Photonics, which spun out of MIT in 2016, hope to break this impasse. We are developing a tiny, chip-scale phased-array lidar that promises to slash costs and simplify integration. Here we'd like to explain some of the technical challenges we've encountered and how very close we are to commercialization.

TODAY, MORE THAN half of new cars are equipped with one or more radar sensors. These sensors are solid state, cost manufacturers less than US $100 each, and are small enough to be inconspicuously placed around the vehicle. They are used for a variety of things, including automatic emergency braking and adaptive cruise control, as well as lane keeping and other advanced driver-assistance functions.

But this wasn't always the case. Early automotive radars were large, mechanically steered, emitted short pulses of radio waves, and had limited performance. But the move to electronic scanning and continuous-wave emissions in automotive radars brought performance advancements and cost reductions, which in turn ushered in their widespread use.

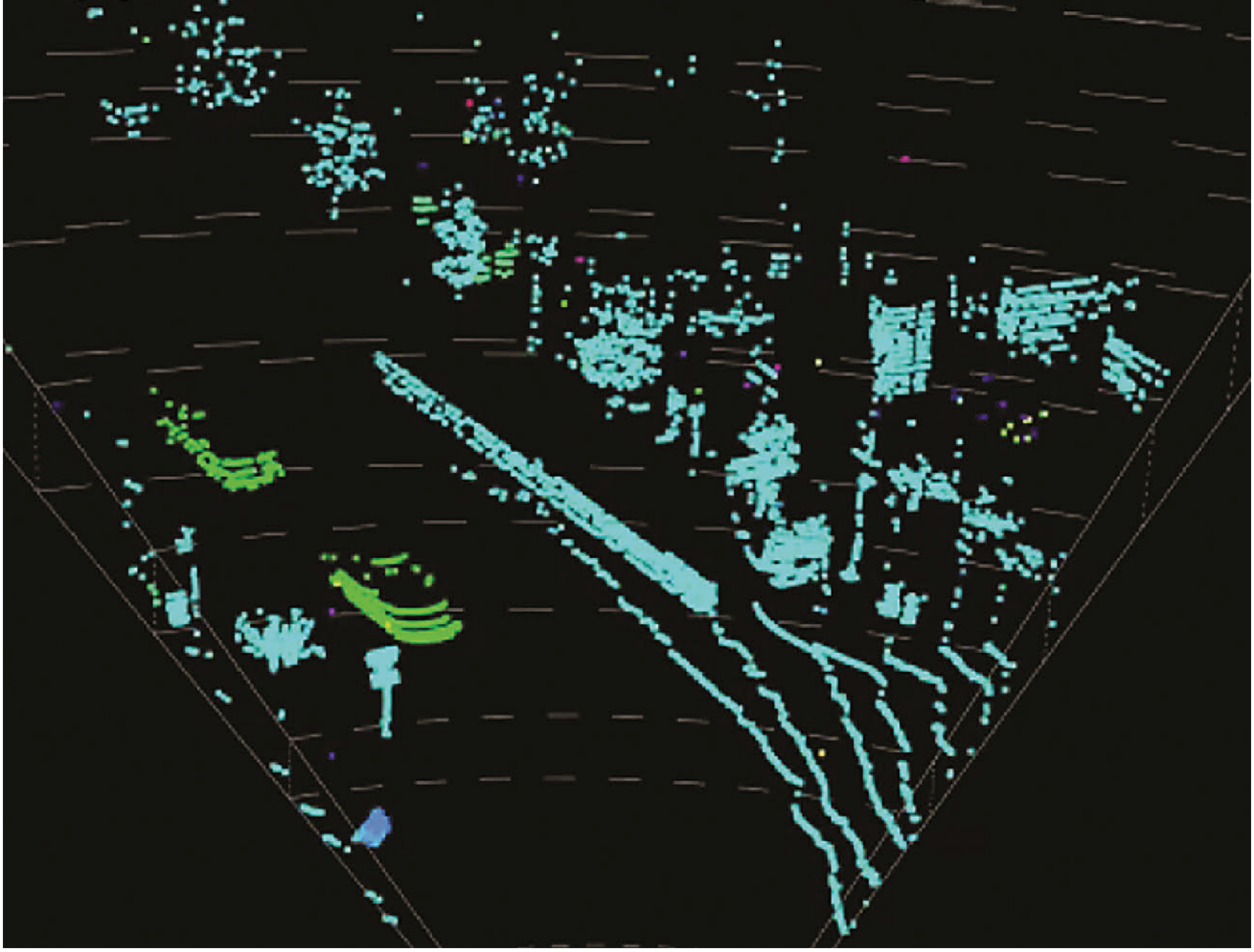
Lidar is now undergoing this same evolution. The technology began making headlines around 2016 as a slew of companies, spurred on by the success of lidar sensors on vehicles entered in the DARPA Grand Challenge a decade earlier, began developing custom systems for autonomous vehicles. These systems tended to be pieced together from off-the-shelf components.

These first-generation lidars went only so far. Spinning or scanning mirrors contributed to their high costs and made their integration into vehicles difficult. They also suffered from reliability issues, and their pulsed operation led to problems in the presence of direct sunlight and resulted in an inherent susceptibility to interference from neighboring lidars. As a result, the available lidar sensors have not met the stringent performance, reliability, and cost goals of the automotive industry.

Carmakers are looking for high-performance, long-range lidar sensors that will cost them less than $500 each. While lidar manufacturers have made

This working prototype for the authors' long-range lidar is much larger than the finished product will be.

ALL IMAGES: ANALOG PHOTONICS



This point-cloud image is based on measurements from the authors' lidar obtained near a busy intersection [photo]. Moving cars are shown in green and static objects in blue.

progress, the industry isn't there just yet.

Our company chose to attack these problems head-on by designing lidar sensors that are built entirely on a chip—a photonic integrated circuit made of ordinary silicon. It has no moving parts and generates, emits, and receives light with no external hardware. And its tiny size makes it easy to incorporate into the bodies of even the sleekest cars on the road.

Lidar is a lot like radar, but it operates in the infrared portion of the spectrum, with wavelengths typically between 905 and 1,550 nanometers (compared with a few millimeters for automotive radar). This difference in wavelength gives lidar much better spatial resolution, because the waves sent out from the sensor can be more tightly focused.

Most early automotive lidars, like most early radars, used what is called time-of-flight (ToF) detection. A short pulse of electromagnetic energy is sent out, hits an object, and then reflects back to the sensor, which measures the time it takes for the pulse to complete this round trip. The unit then calculates the range to the object using the known speed of light in air. These systems all suffer from some inherent limitations. In particular, lidars built on this principle are prone to interference from sunlight and from light pulses coming from other lidars.

Most modern radars systems work differently. Instead of sending out pulses, they emit radio waves continuously. The frequency of these emissions is not fixed. Instead, they are swept back and forth across a range of frequencies.

To understand the reason for doing that, it's important to know what happens when signals of two different frequencies are combined in a way that isn't purely additive. Doing so will generate two new frequencies: the sum and difference of the two frequencies you initially mixed. This process, called heterodyning, was first demonstrated in 1901 and has since been used widely in radio equipment.

Frequency-modulated continuous-wave (FMCW) radars take advantage of the fact that signals of two different frequencies, when mixed in this fashion, give rise to a signal whose frequency is the difference of the first two. In these radars, the mixing is done between the outgoing signal (or, in truth, an attenuated version of it, often called the local oscillator) and the reflected signal, which differ in frequency because the outgoing signal is, as we mentioned, being swept across a range of frequencies. So by the time the reflected signal makes it back to the sensor, the outgoing signal will have a different frequency from what it had when the now-reflected waves first left the radar antenna.

If the reflected signal took a long time to make the round trip, the difference in frequencies will be large. If the reflected signal took only a short time to bounce back, the difference in frequencies will be small. So the difference in frequencies between outgoing and reflected signals provides a measure of how far away the target is.

While they are more complex than ToF-based systems, FMCW systems are more sensitive, essentially immune to interference, and can be used to measure the velocity of a target in addition to its distance.

Automotive lidar is now adopting a similar approach. FMCW lidar involves slightly altering the frequency, and thus the wavelength, of the transmitted light and then combining the backscattered light with a local oscillator at the frequency of the transmitted light. By measuring the frequency difference between the received light and the local oscillator, the system can determine the range to target. What's more, any Doppler shifts from a moving target can also be extracted, revealing the target's velocity toward or away from the sensor.

This capability is useful for quickly identifying moving targets and discriminating among closely spaced objects that are moving at different speeds. The velocity measurement can also be used to predict other vehicle movements and can even sense a pedestrian's gestures. This additional dimension to the data, not available from ToF systems, is why FMCW systems are sometimes called 4D lidar.

As you might imagine, FMCW lidar systems use a very different laser source than ToF systems do. FMCW lidars emit light continuously, and that light has comparatively low peak power. The laser power levels are similar to those used in many communications applications, meaning that the light can be generated and processed by photonic integrated circuits. This tiny laser system is one of the key factors that has enabled chip-based lidars.

THE PHOTONIC integrated circuits we designed can be fabricated on standard 300-millimeter-diameter silicon wafers using photolithography, just as is done for most integrated circuits. So we can take advantage of the maturity of the CMOS semiconductor-manufacturing industry to combine all of the various on-chip optical components needed for a full lidar system: lasers, optical amplifiers, waveguides, splitters, modulators, photodetectors, and, in our case, optical phased arrays.

The economies of semiconductor manufacturing slash the cost of each of these components. Having all of them integrated on a single chip helps, too. You see, all lidar systems both transmit light and receive light, and the transmitting and receiving optics must be well aligned. In systems built with discrete optical components, the need for precise alignment adds complexity, manufacturing time, and cost. When things slip out of alignment, the lidar can fail. With integrated photonics, the precise alignment is inherent, because the waveguides carrying the light are lithographically defined.

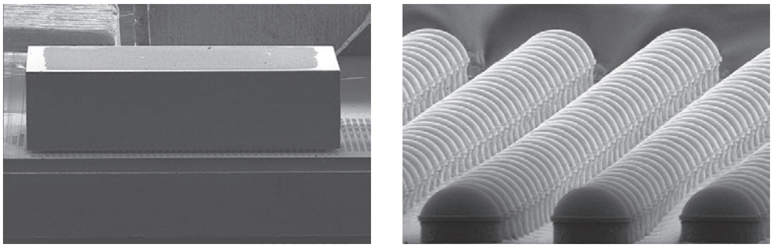
While a handful of companies are working to develop photonic IC–based lidars, only Analog Photonics has figured out how to eliminate the need to mechanically scan the scene with its single-chip lidar. Instead of mechanical scanning, we use what are called optical phased arrays, which allow the beam to be steered electronically.

Scanning is an essential aspect of lidar and one of the key challenges of the technology. The system builds a picture of its surroundings by scanning the scene with one or more laser beams. To detect and identify targets quickly, the lidar must rapidly scan its entire field of view, doing so with sufficiently high resolution to distinguish different objects.

Initially, lidar sensors scanned by either spinning the sensor or introducing rotating mirrors into the beam path. The resulting hardware was cumbersome, expensive, and often unreliable.

Although some radars also point their antennas mechanically—as you have no doubt noticed at airports and marinas—some steer the radar beam electronically using phased antenna arrays. This technique adjusts the phase of the signals leaving each of several antennas in such a way that radio waves interfere with one another constructively in one direction and destructively in other directions. By adjusting signal phases at each antenna, the radar can vary the direction in which these signals combine constructively to form a beam.

Electronically phased arrays are the beam-steering technology of choice for automotive radars. Recognizing that the physics of a phased array applies to all frequencies of the electromagnetic spectrum, including optical frequencies, we decided to use this approach in our solid-state lidar. Aided by the Defense Advanced Research Projects Agency through its Modular Optical Aperture Building Blocks program, and with help from several automotive partners (whose names we can't yet reveal), Analog Photonics has developed on-chip optical phased arrays.



A low-magnification electron micrograph reveals that the lidar consists of two parts: a silicon photonic chip and a semiconductor chip [left]. The latter contains the electronics that control the many photonic elements. A higher-magnification micrograph details the tiny copper bumps that are used to make the electrical connections between these two chips [right].

RECOGNIZING THAT THE PHYSICS OF A PHASED ARRAY APPLY TO ALL FREQUENCIES OF THE ELECTROMAGNETIC SPECTRUM, WE DECIDED TO USE THIS APPROACH IN OUR SOLID-STATE LIDAR.

These renderings show what the lidar models now in development are anticipated to look like. The one on the left is designed for long range with a narrow field of view, whereas the one on the right will operate at short range with a wide field of view.

For these arrays, the top surface of the chip is used as both a transmitting and receiving aperture—that's where the energy leaves and returns to the chip. The on-chip optical phase shifters and emitters are individually controlled with custom electronics to steer exceedingly tight optical beams, ones that are just several millimeters wide.

Achieving a range of steering that's large enough to be useful requires thousands of closely spaced phase shifters. For example, for a lidar that operates at a wavelength of 1,550 nm, the phase shifters must be placed just 1.5 micrometers apart to enable a 60-degree steering range.

You might wonder how all this optical phase shifting is done. It requires altering the optical properties of the transparent material inside the chip's many micrometer-scale optical waveguides, which channel the light from the laser where it is generated to the aperture where it is emitted. If you can change the speed of light in that material, you will alter the phase of the light wave exiting the waveguide.

The material here is just silicon, which is transparent to light at infrared wavelengths. One way to alter the speed of light in silicon is to pass sound waves through it, a technique being pursued for use in lidar by researchers at the University of Washington. Another way is to change the temperature: The hotter the silicon, the more the light passing through it is slowed. This is the principle behind what are called thermo-optic phase shifters.

With thousands of phase shifters on a chip, it's critical that each one consume very little power, mere microwatts. And that's hard to do when you must heat things up. We sidestepped the need for heating by using electro-optic rather than thermo-optic phase shifters. This approach also enabled us to steer the beam faster, allowing it to step across the field of view at rates exceeding one million scan lines per second.

There remained, though, the challenge of how to connect the many closely spaced optical waveguides with the electronics required to adjust the speed of light within them. We solved this using flip-chip technology: One CMOS chip has thousands of solder-coated copper bumps placed about 75 micrometers apart, or about half the width of a human hair. This scheme allows our silicon photonics chip to be permanently mated with a semiconductor electronic chip containing the needed digital logic and a matching set of copper bumps. Simple commands to the electronic chip then drive thousands of photonic components in the appropriate fashion to sweep the beam.

ANALOG PHOTONICS has now built and delivered prototypes of the world's first all-solid-state beam-sweeping lidar to its industry partners, which are companies that supply automotive equipment directly to carmakers. We've solved most of the fundamental and engineering challenges and are now focused on increasing the lidar's performance to meet production specifications. We expect to be turning our creations into actual products and producing large numbers of samples for the automotive industry in 2025.

We are currently working on two different versions of our lidar: a long-range version intended to be mounted at the front of the car for use at highway speeds and a short-range version with a wider field of view to provide complete coverage all around the vehicle. The two sensors have different optical phased arrays in their photonic ICs, while sharing the same back-end signal processing.

We expect that relatively low-cost lidar sensors from some of our competitors, such as Cepton and Luminar, will begin showing up in some top-of-the line cars as early as next year. And driven by the availability of low-cost solid-state sensors like the ones we're working on, lidar will be common in new cars by the end of the decade.

But the future of lidar won't end there. Market forecasters expect lidar to be used for many other applications, including industrial automation and robots, mobile-device applications, precision agriculture, surveying, and gaming. And the kind of work we and others are doing with silicon-photonic ICs should help make that bright, lidar-filled future arrive all the sooner. ■

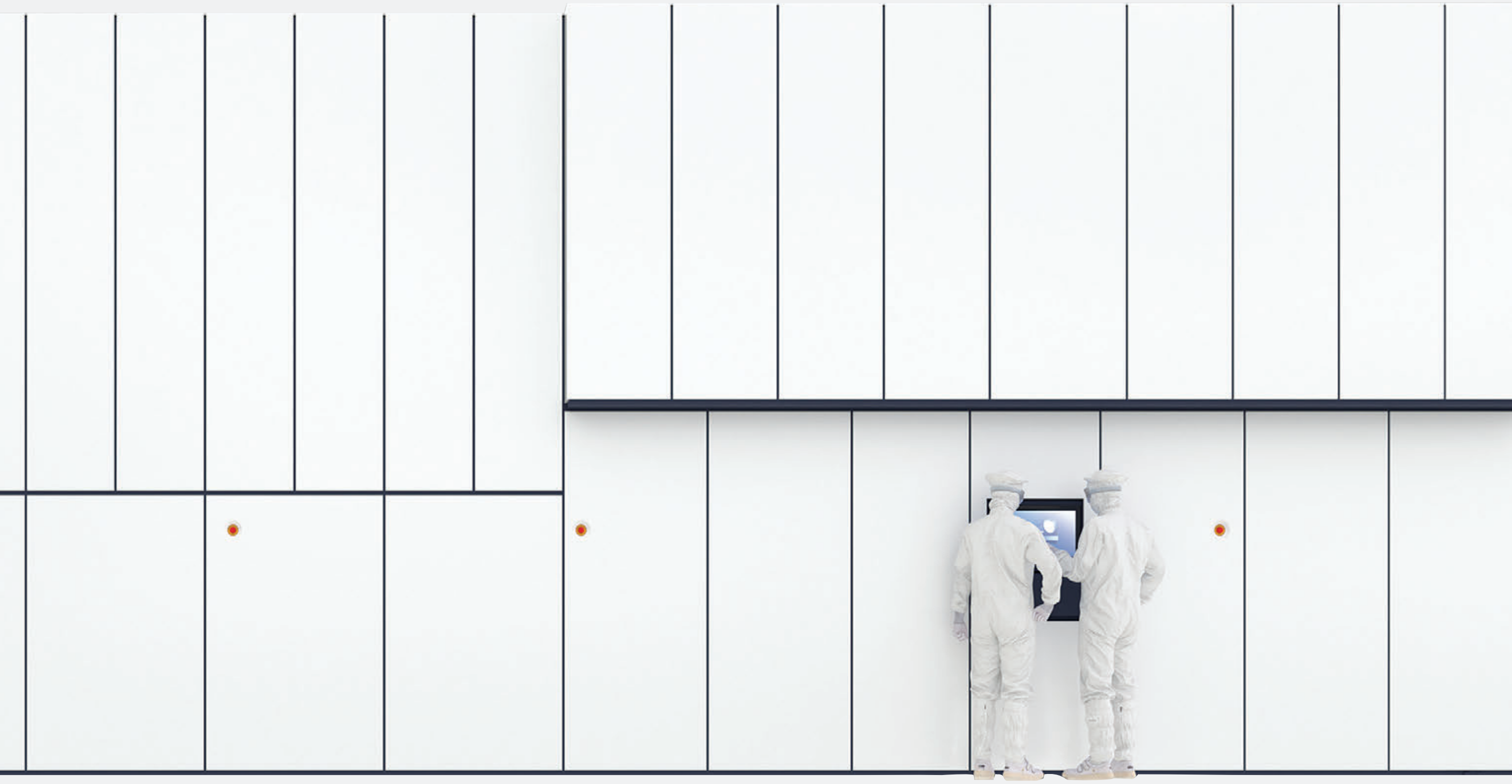
THE MOORE'S LAW MACHINE

BY JAN VAN SCHOOT

This photo-illustration of the EXE:5000, ASML's high-numerical-aperture extreme-ultraviolet-lithography machine, shows its massive scale.

ASML

The next trick to tinier transistors is high-



numerical-aperture EUV lithography

Over the last half-century, we've come to think of Moore's Law—the roughly biennial doubling of the number of transistors in a given area of silicon, the gains that drive computing forward—as something that just happens, as though it were a natural, inevitable process, akin to evolution or aging. The reality, of course, is much different. Keeping pace with Moore's Law requires almost unimaginable expenditures of time, energy, and human ingenuity—thousands of people on multiple continents and endless acres of some of the most complex machinery on the planet. ● Perhaps the most essential of these machines performs extreme-ultraviolet (EUV) photolithography. EUV lithography, the product of decades of R&D, is now the driving technology behind the past two generations of cutting-edge chips, used in every top-end smartphone, tablet, laptop, and server in the last three years. Yet Moore's Law must march on, and chipmakers continue to advance their road maps, meaning they'll need to shrink device geometries even further. ● So at ASML, my colleagues and I are developing the next generation of lithography. Called high-numerical-aperture EUV lithography, it involves a major overhaul of the system's internal optics. High-NA EUV should be ready for commercial use in 2025, and chipmakers are depending on its capabilities to keep their promised advances through the end of this decade.

Moore's Law relies on improving the resolution of photolithography so that chipmakers can lay down finer and finer circuits. Over the last 35 years, engineers have achieved a resolution reduction of two orders of magnitude by working on a combination of three factors: the wavelength of the light; k_1, a coefficient that encapsulates process-related factors; and numerical aperture (NA), a measure of the range of angles over which the system can emit light.

The critical dimension—that is, the smallest possible feature size you can print with a certain photolithography-exposure tool—is proportional to the wavelength of light divided by the numerical aperture of the optics. So you can achieve smaller critical dimensions by using either shorter light wavelengths or larger numerical apertures, or a combination of the two. The k_1 value can be pushed as close as possible to its physical lower limit of 0.25 by improving manufacturing-process control, for example.

In general, the most economical ways to boost resolution are by increasing the numerical aperture and by improving tool and process control to allow for a smaller k_1. Only after chipmakers run out of options to further improve NA and k_1 do they resort to reducing the wavelength of the light source.

$$CD = k_1 \frac{\lambda}{NA}$$

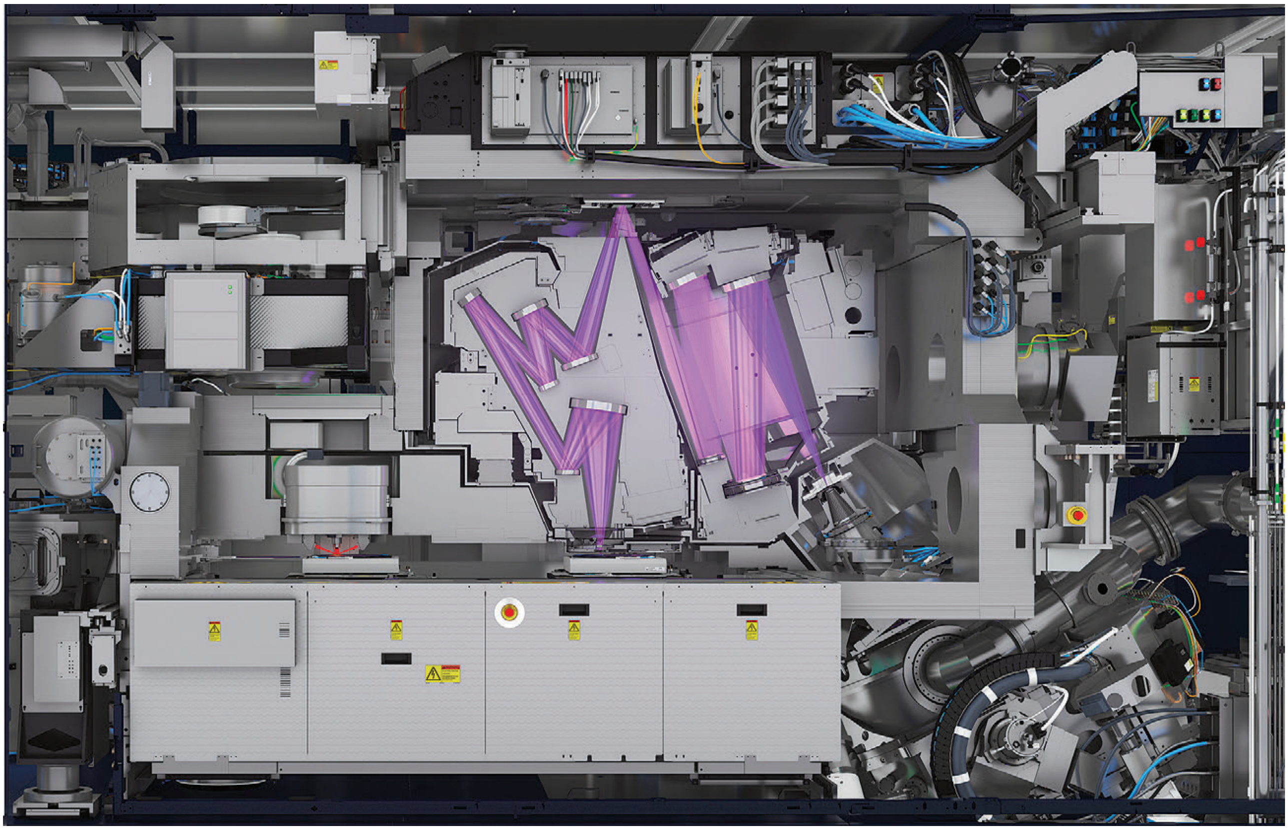
The critical dimension—the resolution of a photolithography system—is equal to the wavelength of light used divided by the numerical aperture and multiplied by a quality, k_1, related to process improvements.

Nevertheless, the industry has had to make that wavelength change a number of times. The historical progression of wavelengths went from 365 nanometers, generated using a mercury lamp, to 248 nm, via a krypton-fluoride laser, in the late 1990s, and then to 193 nm, from an argon-fluoride laser, at the beginning of this century. For each generation of wavelength, the numerical aperture of lithography systems was progressively increased before industry jumped to a shorter wavelength.

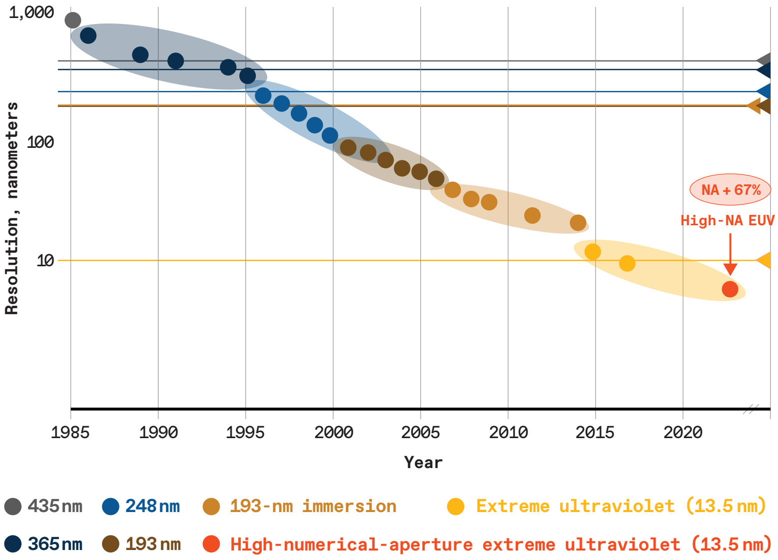
For example, as the use of 193 nm was coming to an end, a novel approach to increasing NA was introduced: immersion lithography. By placing water between the bottom of the lens and the wafer, the NA could be significantly enlarged from 0.93 to 1.35. From its introduction around 2006, 193-nm immersion lithography was the industry workhorse for leading-edge lithography .

But as the need to print features smaller than 30 nm increased, and because the NA of 193-nm lithography had been maxed out, keeping up with Moore's Law grew more and more complex. To create features smaller than 30 nm requires either using multiple patterns to produce a single layer of chip features—a technologically and economically burdensome technique—or another change of wavelength. It took more than 20 years and an unparalleled development effort to bring the next new wavelength on line: 13.5-nm EUV.

EUV necessitates an entirely new way to generate light. It's a remarkably complex process that involves hitting molten tin droplets in midflight with a powerful CO_2 laser. The laser vaporizes the tin into a plasma, emitting a spectrum of photonic energy. From this spectrum, the EUV optics harvest the required 13.5-nm wavelength and direct it through a series of mirrors before it is reflected off a patterned mask to project that pattern onto the wafer. And all of this must be done in an ultraclean vacuum, because the 13.5-nm wavelength is absorbed by air. (In previous generations of photolithography, light was directed through the mask to project a pattern onto the wafer. But EUV is so readily absorbed that the mask and other optics must be reflective instead.)



In a vacuum chamber, EUV light [purple] reflects off of multiple mirrors before bouncing off of the photomask [top center]. From there the light continues its journey until it is projected onto the wafer [bottom center], carrying the photomask's pattern. The illustration shows today's commercial system with a 0.33 numerical aperture. The optics in future systems, with an NA of 0.55, will be different.

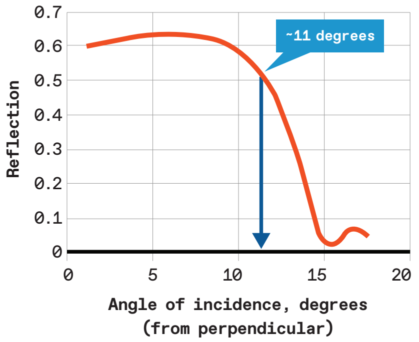


The resolution of photolithography has improved by about two orders of magnitude over the last 35 years. That's due in part to using smaller and smaller wavelengths of light, but it has also required greater numerical aperture and improved processing techniques.

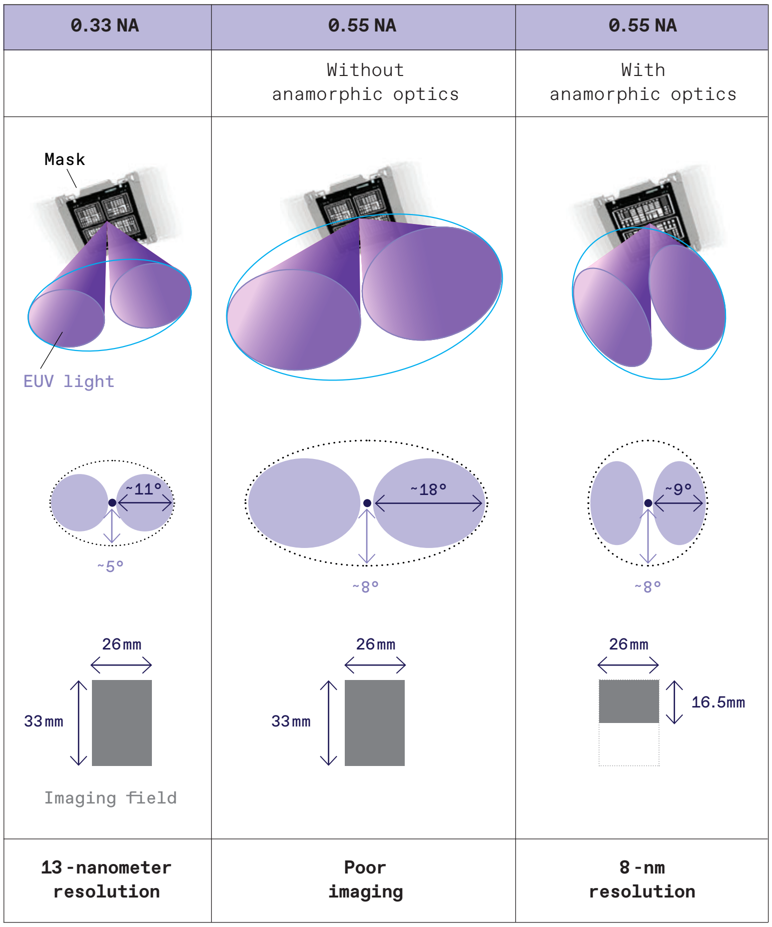
ASML

The switch to EUV from 193-nanometer light did part of the job of decreasing the critical dimension. A process called "design for manufacturing," which involves setting the design rules of circuit blocks to take advantage of photolithography's limits, has done a lot to reduce k_1. Now it's time to boost numerical aperture again, from today's 0.33 to 0.55.

Increasing the NA from 0.33 to the target value of 0.55 inevitably entails a cascade of other adjustments. Projection systems like EUV lithography have an NA at the wafer and also at the mask. When you increase the NA at the wafer, it also increases the NA at the mask. Consequently, at the mask, the incoming and outgoing cones of light become larger and must be angled away from each other to avoid overlapping. Overlapping cones of light produce an asymmetric diffraction pattern, resulting in unpleasant imaging effects.



If the EUV light strikes the photomask at too steep an angle, it will not reflect properly.



The angle of reflection at the mask in today's EUV is at its limit [left column]. Increasing the numerical aperture of EUV would result in an angle of reflection that is too wide [center]. So high-NA EUV uses anamorphic optics, which allow the angle to increase in only one direction [right]. The field that can be imaged this way is half the size, so the pattern on the mask must be distorted in one direction, but that's good enough to maintain throughput through the machine.

But there's a limit to this angle. Because the reflective masks needed for EUV lithography are actually made of multiple layers of material, you can't ensure getting a proper reflection above a certain reflective angle. EUV masks have a maximum reflective angle of 11 degrees. There are other challenges as well, but reflective angle is the biggest.

The only way to overcome this challenge is to increase a quality called demagnification. Demagnification is exactly what it sounds like—taking the reflected pattern from the mask and shrinking it. To compensate for the reflective-angle problem, my colleagues and I had to double the demagnification to 8x. As a consequence, the part of the mask imaged will be much smaller on the wafer. This smaller image field means it will take longer to produce the complete chip pattern. Indeed, this requirement would reduce the throughput of our high-NA scanner to under 100 wafers per hour—a productivity level that would make chip manufacturing uneconomical.

Thankfully, we found that it is necessary to increase the demagnification in only one direction—the one in which the largest reflective angles occur. The demagnification in the other direction can remain unchanged. This results in an acceptable field size on the wafer—about half the size used in today's EUV systems, or 26 by 16.5 millimeters instead of 26 by 33 mm. This kind of direction-dependent, or anamorphic, demagnification forms the basis of our high-NA system. The optics manufacturer Carl Zeiss has made a herculean effort to design and manufacture an anamorphic lens with the specifications required for our new machine.

To ensure the same productivity levels with the half-size field, we had to redevelop the system's reticle and wafer stages—the platforms that hold the mask and wafer, respectively, and move them in sync with each other as the scanning process takes place. The redesign resulted in nanometer-precision stages with acceleration improved by a factor of four.

The first high-NA EUV system, the ASML EXE:5000, will be installed in a new lab that we're opening jointly with the Belgium-based nanoelectronics research facility Imec, in early 2024. This lab will allow customers, mask makers, photoresist suppliers, and others to develop the infrastructure needed to make high-NA EUV a reality.

And it is essential that we do make it a reality, because high-NA EUV is a critical component in keeping Moore's Law alive. Getting to 0.55 NA won't be the final step, though. From there, ASML, Zeiss, and the entire semiconductor ecosystem will be stretching even further toward technologies that are better, faster, and innovative in ways we can hardly imagine yet. ■

THE INSTITUTE

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Aart de Geus: The Maestro Who Revolutionized Chip Design P. 52

The CT Scanner Made Brain Imaging Possible **P. 62**

Airport Robots Deliver Food Right to the Gate **P. 65**

IAN C. BATES/THE NEW YORK TIMES/REDUX

IEEE President Saifur Rahman at the European Parliament in Brussels, where he participated in events on sustainability.

SAIFUR RAHMAN

Forging Partnerships Will Sharpen IEEE's Edge

AS I SHARED in the March column, my goal as IEEE president is to work with all members—particularly students, young professionals, and affinity group members—to make IEEE a more successful and resilient global technical organization. I also want the organization to be globally recognized as a force for change. To reach these goals, I have been defining objectives that engage our members.

This year, I chartered four ad hoc committees: climate change, innovative funding models, president-elect campaign pilot program, and multimedia-based digital reality technologies. These member-led committees are helping IEEE focus on items of concern and create well-coordinated road maps to help develop programs and positions to carry out its mission of public service.

To make IEEE more relevant to young professionals and women technologists, I have strived to help increase participation and engagement within their affinity groups. In fact, I am a member of IEEE Women in Engineering because I believe it is an organization for women, not of women.

I have had the opportunity to attend and speak at both WIE and IEEE Young Professionals meetings, and I encourage constant contact with the group's leadership. These engagements at the grassroots level provide better insights into understanding the community's needs and what resources could help advance members' professional lives.

I would like to see IEEE engage more broadly with international organizations to provide technologists additional opportunities to contribute for the benefit of humanity. For example, IEEE is now engaged closely with the U.N. Framework Convention on Climate Change, which is tasked with supporting the global response to the threat of climate change.

I spoke at the UNFCCC Conference of Parties (COP27) last year and will be speaking at COP28 in the United Arab Emirates in December. Such engagements highlight how IEEE's global community of engineers and technologists is using its expertise to help develop solutions to address critical climate change issues.

In July, I spoke at two prominent sustainability and green transition–related events in Europe: the EU Green Week and the European Sustainable Energy Week (EUSEW). The events, both held in Brussels, focused on renewable energy, sustainable development, and green skills, the knowledge, abilities, and attitudes needed to live in, develop, and support a sustainable and resource-efficient society.

EU Green Week, which is organized by the European Commission's Directorate-General for Environment, promotes environmental policies on biodiversity, the circular economy, and eliminating pollution.

EUSEW is the largest annual event dedicated to renewables and efficient energy use in Europe. It is organized by the European Climate, Infrastructure, and Environment Executive Agency (CINEA) and the Directorate-General for Energy.

I also participated in discussions at the European Parliament and the European Commission on the skillsets engineers and technologists need to work in the renewable energy sector and shared examples and use cases from around the world to highlight ways to address the need for new skills.

Those events were excellent opportunities to speak with policymakers, leading environmentalists, and stakeholders from Europe and beyond, and to learn about actions being taken to protect and restore our environment for present and future generations.

I had the opportunity to engage with members of the IEEE European Public Policy Committee's Working

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Group on Energy in discussions about the continent's developments and priorities in the field of green transition and energy. I also held fruitful discussions on the importance of climate-related data and the challenges around accessing, using, and comparing data with representatives from the European Commission's Directorate-Generals of Energy, Climate Action, and Communications Networks, Content, and Technology. We explored ways IEEE can collaborate with these groups based on the strength of our worldwide network and technical expertise.

To support my goal of developing closer and more purposeful relationships with industry leaders, I met with representatives from Huawei, Schneider Electric, and VMWare. I also met with UNIDO, the U.N. Industrial Development Organization, which assists countries in economic and industrial development; and ICLEI, a global network of more than 2,500 local and regional governments committed to sustainable urban development. Key topics of discussion were the technical and professional skills needed in the green digital transition and the importance of building a skilled workforce required to power this transition.

IEEE certainly has a role to play in addressing the growing demand for expertise in sustainable development, as well as training engineers and technical professionals to meet this need. The green transition is a cross-cutting policy issue that requires the inclusion of those who might be excluded from green-growth sectors and green jobs, such as young professionals, women, and members of underrepresented communities.

Developing a strong strategy that aims to create a sustainable digital economy can create new job opportunities and promote economic growth while also reducing the environmental impact.

—SAIFUR RAHMAN
IEEE president and CEO

Please share your thoughts with me at president@ieee.org.

They Turned Adversity to Advantage

Threatened with job loss, these engineers rebounded

HUNDREDS OF THOUSANDS of tech workers have lost their job this year. The members featured in this issue experienced similar periods of employment uncertainty during their career—which pushed them to pursue other options. We hope members who recently lost their job will be uplifted by their success stories.

While working at General Electric in the 1980s, Aart de Geus was developing tools to design logic with multiplexers. He helped write the first program for synthesizing circuits optimized for both speed and area. Worried about losing his job after GE announced it was leaving the semiconductor business, he and two others from his team launched their own company, Synopsys. It is now the largest supplier of software that engineers use to design chips, and de Geus, an IEEE Fellow, is considered a founding father of electronic design automation.

On page 52, learn the ingredients for running a successful company from the guitar-playing chief executive.

John Brooks Slaughter probably is best known as the first African American director of the U.S. National Science Foundation. Appointed by President Carter in 1980, Slaughter aimed to bolster funding for science education and make academia more inclusive by championing science programs at historically Black colleges and universities. But a new U.S. administration cut all funding for Slaughter's initiatives and reduced funding for science education in general. It led him to leave the agency in 1982 to become chancellor of the University of Maryland, the first Black person to hold that position.

On page 56, find out more about the Life Fellow's work to champion diversity in science, technology, engineering, and mathematics during his illustrious career.

Researcher Godfrey Hounsfield was warned that his job at Electrical and Musical Industries (now known as EMI) was in jeopardy if he didn't come up with a good idea for a new product. Hounsfield worked with neuroradiologists to develop the first computed tomography scan of a human brain. Unveiled in 1971, CT scans are now used routinely to pinpoint blood clots, tumors, and bone fractures.

In 1979 Hounsfield shared the Nobel Prize in physiology or medicine for the invention. Read about the IEEE Milestone for the CT scanner on page 62.

For members who've lost their job, on page 59 we've listed IEEE resources designed to help you sharpen your skills and find your next position.

Despite all the recent layoffs, de Geus says he believes engineering is a great career: "Just because a few companies have overhired or are redirecting themselves doesn't mean that the engineering field is in a downward trend. I would argue the opposite, for sure in the electronics and software space, because the vision of 'smart everything' requires some very sophisticated capabilities."

—KATHY PRETZ
Editor in chief, *The Institute*

For updates about IEEE and its members, visit us at spectrum.ieee.org/the-institute

De Geus proudly displays the company's "Yes, if …" mantra to combat the "No, because …" mindset to remind employees to think about what is possible instead of what is not.

IAN C. BATES/THE NEW YORK TIMES/REDUX

PROFILE

Aart de Geus Transformed IC Design

The Synopsys CEO helped create logical synthesis

BY KATHY PRETZ

FOR SYNOPSYS CHIEF Executive Aart de Geus, running the electronic design automation behemoth is similar to being a bandleader. He brings together the right people, organizes them into a cohesive ensemble, and then leads them in performing their best.

De Geus, who helped found the company in 1986, has some experience with bands. The IEEE Fellow has been playing guitar in blues and jazz bands since he was an engineering student in the late 1970s.

Much like jazz musicians improvising, engineers go with the flow at team meetings, he says: One person comes up with an idea, and another suggests ways to improve it.

"There are actually a lot of commonalities between my music hobby and my other big hobby, Synopsys," de Geus says.

Synopsys, the largest supplier of software that engineers use to design chips, employs about 20,000 people. The company reported US $1.395 billion in revenue in the second quarter of this year.

De Geus is considered a founding father of electronic design automation (EDA), which automates chip design using synthesis and other tools. He and his team pioneered it in the 1980s. Synthesis revolutionized digital design by taking the high-level functional description of a circuit and automatically selecting the logic components (gates) and constructing the connections (netlist) to build the circuit. Virtually all large digital chips manufactured today are mostly synthesized, using software that de Geus and his team developed.

"Synthesis changed the very nature of how digital chips are designed, moving us from the age of computer-*aided* design (CAD) to electronic design *automation*," he says.

During the past three and a half decades, logic synthesis has enabled about a 10 millionfold increase in chip complexity, he says.

The first circuit synthesizer

Born in Vlaardingen, Netherlands, de Geus grew up mostly in Basel, Switzerland. He earned a master's degree in electrical engineering in 1978 from the École Polytechnique Fédérale de Lausanne, known as EPFL.

In the early 1980s, while pursuing a Ph.D. in electrical engineering from Southern Methodist University, in Dallas, de Geus joined General Electric in Research Triangle Park, N.C.

There he developed tools to design logic with multiplexers, according to a 2009 oral history conducted by the Computer History Museum. He and a designer friend created gate arrays with a mix of logic gates and multiplexers.

That led to writing the first program for synthesizing circuits optimized for both speed and area, known as SOCRATES. It automatically created blocks of logic from functional descriptions, according to the oral history.

"The problem was [that] all designers coming out of school used Karnaugh maps, [and] knew NAND gates, NOR gates, and inverters," de Geus explained in the oral history. "They didn't know multiplexers. So designing with these things was actually difficult." Karnaugh maps are a method of simplifying Boolean algebra expressions. With NAND and NOR universal logic gates, any Boolean expression can be implemented without using any other gate.

SOCRATES could write a function and 20 minutes later, the program would generate a netlist that named the electronic components in the circuit and the nodes they connected to. By automating the function, de Geus says, "the synthesizer typically created faster circuits that also used fewer gates. That's a big benefit because fewer is better. Fewer ultimately end up in [a] smaller area on a chip."

With that technology, circuit designers shifted their focus from gate-level design to designs based on hardware description languages.

De Geus was promoted to manager of GE's Advanced Computer-Aided Engineering Group. Then, in 1986, the company decided to leave the semiconductor business. Facing the loss of his job, he decided to launch his own company to continue to enhance synthesis tools.

He and two members of his GE team, David Gregory and Bill Krieger, founded Optimal Solutions in Research Triangle Park. In 1987 the company was renamed Synopsys and moved to Mountain View, Calif.

Building a good team

De Geus says he picked up his management skills and entrepreneurial spirit as a youngster. He usually was the team leader, he says, the one with plenty of imagination.

"An entrepreneur creates a vision of some crazy but, hopefully, brilliant idea," he says, laughing. The vision sets the direction for the project while the entrepreneur's business side tries to convince others that the idea is realistic enough.

"If you have a good team, everybody chips in something," he says. "Before you know it, someone on the team has an even better idea of what we could do or how to do it."

At Synopsys, de Geus sees himself as "the person who makes the team cook. It's being an orchestrator, a bandleader, or maybe someone who brings out the passion in people who are better in both technology and business. As a team, we can do things that are impossible to do alone and that are patently proven to be impossible in the first place."

He says a few years ago the company came up with the mantra "Yes, if ..." to combat a slowly growing "No, because ..." mindset.

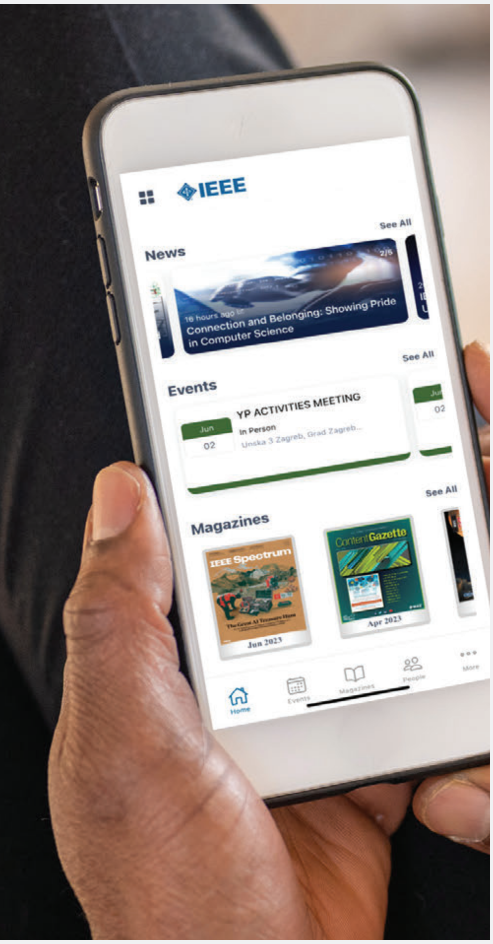
"'Yes, if ...' opens doors, whereas the 'No, because ...' says, 'Let me prove that it's not possible,'" he says. "'Yes, if ...' leads us outside the box into 'It's got to be possible. There's got to be a way.'"

De Geus joined IEEE because one of his EPFL professors encouraged him to do so, in part so that he could attend the organization's conferences.

He says what he values most about IEEE membership is connecting with like-minded people. "That's how all kinds of different ideas come out and fertilize each other," he says. "IEEE is a fulcrum for that." ■

Employer
Synopsys, Sunnyvale, Calif.
Title CEO
Member grade
Fellow
Alma mater
Southern Methodist University, in Dallas

> "Synthesis changed the very nature of how digital designs are being constructed."



IEEE PRODUCTS

The IEEE Mobile App Connects Engineers Worldwide

BY KATHY PRETZ

IF YOU WORK from home or have relocated to a new city, it can be more difficult to network with other engineers and the global technology community. The IEEE app can help. More than 1 million people are already using it.

One of its many features is connecting app-using members who have similar interests or affiliations, or live nearby. The app lets users schedule, manage, and join meetups virtually.

Another popular way to network with others is at IEEE events. The app can recommend upcoming conferences and meetings based on your interests and location. Or you can use the event-finder feature, which filters the search results by location, date, and topic. The app provides the name of the event, its duration, and location, as well as whether the meeting is in person, virtual, or a combination of in person and online. Users can add events to their calendar or bookmark them.

The IEEE Collabratec networking platform is accessible through the app. Members can join communities established around technical interests; geographic locations; companies; universities; and IEEE groups, regions, sections, and societies.

To keep users up to date with tech news, the app includes feeds from IEEE news outlets including *IEEE Spectrum* and *The Institute*.

Users also can access their IEEE publication subscriptions and either download the publications or read them on their mobile device.

Under the app's Discover menu, users can find trusted research published in the IEEE Xplore Digital Library, learn about technical standards, and check out hundreds of continuing education courses.

Members also can keep up to date on what technical solutions IEEE and its members are working on to address the climate crisis.

The IEEE President's Corner contains updates from the organization's top leader.

All the personalized features require permission from users to share their information.

You can download the IEEE app from Apple's App Store or Google Play. ■

IEEE SERVICES

Elevate Your Career With the IEEE Mentoring Program

BY KATHY PRETZ

Members, would you like to provide advice to a young professional? Or are you a student who would like to know more about a specific technical discipline from someone with experience? Consider participating in the IEEE Mentoring Program offered by IEEE Collabratec.

The online networking and collaboration program helps pair members who want to be mentors with those who are seeking guidance on topics such as their career, education, leadership, volunteering, or a particular technical field.

Participation in the program is open to all IEEE members including students.

Before getting started, review the IEEE Mentoring Program guidelines to learn about the shared responsibilities between the mentor and mentee, as well as best practices.

After logging in to your IEEE Collabratec account, go to your profile, which can be found on the settings page. Members' profiles are automatically populated with information such as location, education, IEEE society memberships, and volunteer positions. From the Edit button on the profile page, information such as technical interests and technical expertise can be added.

Make sure your profile is visible by using the Edit Privacy button to set it to IEEE member.

Once you've finished those steps, activate your mentor or mentee status.

Mentors then fill in their mentee preferences and wait for a request from a prospective mentee. Mentees are presented with a list of all mentors.

When mentees find someone, they should click the Mentor Request button.

A mentoring partnership status console is displayed on the Career Services page, with the pending partnership listed as well as the pending request form available for review by the mentor. Once a mentor accepts a request, the partnership status changes to active. ■

ISTOCK/IEEE SPECTRUM

ISTOCK

NEWS

Preparing IEEE for 2050 and Beyond

Leaders are reviewing membership models and product offerings

BY KATHY PRETZ

LAST YEAR 2022 IEEE President and CEO K.J. Ray Liu formed the Ad Hoc Committee on IEEE in 2050 to assist the organization in meeting the needs of the future by planning now. The committee was tasked with identifying the changes the organization might need to make while beginning to develop long-term strategies for the future. It released its findings in the “IEEE in 2050 and Beyond” white paper.

Here is a summary of the recommendations.

Governance and organization

IEEE should rethink the structure of the organization’s governance to increase its ability to be adaptable, agile, and flexible, and to act with speed. The white paper recommends that the Board of Directors conduct research to explore future governance and organizational structures.

Engagement and membership

Traditional membership in IEEE is likely to decline. Membership is apt to be more diverse and interdisciplinary, and future members will have broader and more diverse backgrounds, the report says.

The way IEEE interacts with members will have to change. Building online platforms that allow people to quickly access what they want will be important. The committee expects most gatherings in the future will incorporate artificial intelligence, virtual reality, and digital twins, which are virtual models of a real-world object or system that can be used to assess how the real-world counterpart is performing. Making use of those technologies to organize meetings, including ones held virtually, will create more opportunities for engagement.

Despite the growth in virtual gatherings, there will still be value in physical participation in local and global gatherings, the report said. By 2050 the integration of in-person and virtual attendance is expected to be seamless.

IEEE should continue to explore the organization’s potential future engagement and membership models, and their revenue sources.

Future products and services

IEEE will likely maintain its reputation as a trusted, neutral provider of quality, peer-reviewed content. But how the information is curated and delivered will change, according to the report. The initial vetting of content, for example, probably will be either partially or fully automated.

The committee expects that future content will be a compendium of articles, algorithms, videos, and other media. Access to some of the material might require users to pay a fee.

To become more meaningful to a broader audience, the white paper recommends that IEEE should focus more on how research can be applied. Also IEEE should explore intelligent search-application services in collaboration with developers for artificial intelligence, augmented reality, and virtual reality.

The committee anticipates that IEEE will continue to support the educational and capacity-building needs of people who use science, technology, engineering, and mathematics—related products and services through on-demand offerings that include text, images, and audio.

More relevant technical standards

IEEE’s standards activity is likely to remain important because technological innovation is happening so rapidly. But standards development also needs to evolve and accelerate to address the rapid changes in technology, the report says.

The committee’s report recommends that IEEE research how it brings together its different services and products to address mission-based topics that interest its constituents and new stakeholders.

New funding opportunities

Membership-related income could change from a dues-paying model to a subscription-based one, according to the white paper. Instead of depending on member dues, IEEE could consider revenue streams such as skill-building programs and sponsored activities.

Corporate membership could become a substantial revenue stream. Charging for access to IEEE’s research data or to its experts could help the organization thrive, according to the report. ■

The committee has formed six subgroups to explore opportunities presented in the report.

The Courage of Conviction

John Brooks Slaughter risked his career to champion diversity in STEM

BY WILLIE D. JONES

UNIVERSITY OF SOUTHERN CALIFORNIA

JOHN BROOKS SLAUGHTER has been tireless in his efforts to open doors to underrepresented minorities and women in the science, technology, engineering, and mathematics fields. The IEEE Life Fellow has broken barriers and been recognized for his leadership in industry, academia, and government.

Slaughter, probably best known as the first African American director of the U.S. National Science Foundation, was awarded the IEEE Founders Medal in 2022 in recognition of his "leadership and administration significantly advancing inclusion and racial diversity in the engineering profession across government, academic, and nonprofit organizations."

His commitment to the cause of equity and inclusion is so strong that he risked his career to advocate for those attempting to follow in his footsteps.

NSF director resignation

Slaughter was appointed NSF director in 1980. President Jimmy Carter had enthusiastically supported Slaughter's efforts to bolster funding for science education as well as his desire to make the foundation's support for academia more inclusive. Under his leadership, the NSF had been a strong supporter of science programs at historically Black colleges and universities (HBCUs).

"I was the first director of the foundation to visit a number of historically Black colleges and universities," Slaughter says.

Years earlier, when Slaughter was associate director at the NSF, he noticed that HBCUs and less-prestigious predominantly white institutions did not receive the same consideration of their grant applications for funding new facilities and equipment that some of the nation's most prestigious schools enjoyed. When he became director, he set about fixing that.

"I made every effort to make them realize that they could be successful in competing for grants at the NSF," he says.

“These are the ingredients of a successful person: You must be willing to work hard. You have to be resilient and willing to commit yourself so strongly that regardless of how daunting the challenge, you can overcome it.”

In 1980, however, Ronald Reagan was elected president, and his administration saw no use for such efforts, Slaughter says. It set about eliminating all funding for diversity initiatives, in particular, and funding for science education in general.

Throughout 1981, Slaughter walked a tightrope, taking the expected public stance in support of the Reagan administration’s desire to eradicate funding for science education while keeping up a clandestine effort to thwart the gutting of important programs.

But he called a halt to his highwire act in 1982. In one of the great unsung acts of courage carried out by a government employee, Slaughter wrote an alternative version of the testimony he was supposed to give at an appropriations hearing before the U.S. House of Representatives’ science subcommittee on research and technology. It had been vetted by Reagan administration functionaries and submitted to the congressional committee.

He fully understood the risk he was taking, he says. There he was, the first Black man to be appointed the nation’s chief science officer, adhering to his integrity instead of bowing to political expediency. That day, Slaughter expressed his personal views.

“And, of course,” he recalls, “this led to a considerable amount of backlash from the Reagan administration.”

Having made it clear that he was not on board with the new administration’s vision, he says, “I was convinced that I could not continue.”

His potentially career-ending risk was swiftly rewarded. He had received an invitation from the University of Maryland to become chancellor of its College Park campus. He resigned his directorship and took the position.

The shift from government to academia allowed him to continue with his mission to pave the way for the next generation of scientists and engineers to achieve what he had in his career—and perhaps more.

Unshakable faith

The fuel that powered his personal mission came from a life spent overcoming obstacles.

Slaughter was born in 1932 in Topeka, Kan. His mother, a high-school graduate, was a homemaker. His father, who had an elementary-school education, worked odd jobs such as custodial work and running a used-furniture business.

“I was a curious kid,” Slaughter recalls, “and I liked to build things. I made a lot of my own toys and games because we couldn’t really afford much. We weren’t poor, but we didn’t have a lot of money, so I built radios and cameras and various electronic devices. I fell in love with what came to be engineering. That’s why I decided to study engineering in school.”

Employer Retired, professor emeritus of education and computer engineering, University of Southern California

Member grade
Life Fellow

Alma maters
Kansas State University; University of California, Los Angeles; and University of California, San Diego

Asked what gave him the faith in himself that it took to make it through the rigors of engineering school at Kansas State University, in Manhattan, and eventually a doctoral program in engineering science at the University of California, San Diego, he says: “I have to give almost all the credit for what I’ve become to my parents. My dad and mother did not necessarily understand what I was doing, but they supported me. They believed in me, and they gave me the confidence to do whatever it is that I felt that I wanted to do. They were really the major factors.”

A community of advocates

Slaughter spent two years at Washburn University, in Topeka, where he took liberal arts courses. It had a big impact on his life. “I think that’s why I became more of the engineering manager/engineering administrator/scientific administrator, and then ultimately a college president,” he says.

He graduated from Kansas State in 1956 with a bachelor’s degree in engineering. He then attended the University of California, Los Angeles, where he earned a master’s degree in engineering in 1961.

His first job was in San Diego at General Dynamics’ Convair division, which made military aircraft. From there, he moved on to the information systems technology department in the U.S. Navy Electronics Laboratory, also in San Diego. There, Slaughter’s supervisor encouraged him to get a doctorate.

“He told me that if I wanted his job, I would have to get a Ph.D., so I began exploring nearby universities,” Slaughter says. He chose UCSD.

On the day he defended his dissertation, he got the job of director at the lab.

What followed was a string of successful prestigious administrative posts. These included director of the Applied Physics Laboratory at the University of Washington, assistant director in charge of the NSF's Astronomical, Atmospheric, Earth and Ocean Sciences Division (now called the Division of Atmospheric and Geospace Sciences), academic vice president and provost of Washington State University, and chancellor at the University of Maryland.

He became president of Occidental College, in Los Angeles, and he transformed the school into one of the nation's most diverse liberal arts colleges. He went on to teach graduate education courses in diversity and leadership at the University of Southern California for a year.

He then became president and CEO of the National Action Council for Minorities in Engineering, in Alexandria, Va. From 2000 to 2009, he focused his efforts on the same initiatives he prioritized as NSF director. In 2010 he returned to USC to teach courses on leadership, diversity, and technological literacy.

Slaughter has been writing his memoir since he retired in 2022 after a 12-year stint teaching at the Rossier graduate school of education at USC.

"I always tell young people these are the ingredients of a successful person: You must be willing to work hard. You have to be resilient and willing to commit yourself so strongly that regardless of how daunting the challenge, you can overcome it." ■

IEEE Smart Village Lights Up Lives

IEEE SMART VILLAGE, established in 2009, brings electricity as well as access to education and job opportunities to remote, off-the-grid communities worldwide. Here is a look at ISV's impact as of May.

74
projects completed

200,000
customers given access to electricity

US $5.5
million granted in funding

200
volunteers

14
active projects

700
businesses launched after receiving access to power

7,000
photovoltaic solar panels installed at schools, businesses, and homes

Regions where ISV working groups are located

- Africa
- China
- Latin America
- North America
- South Asia

NEWS

THE INSTITUTE GARNERS TWO AWARDS

The publication received an Apex Grand Award for Publication Excellence in the Magazines, Journals, and Tabloids category for its June 2022 print issue. *The Institute* also received an Apex Award in the Writing Diversity, Equity, and Inclusion category for "Leading the Way for More LGBTQ Inclusivity in STEM." The article, written by Associate Editor Joanna Goodrich, profiled Senior Member Arti Agrawal.

ISTOCK

Photo-illustration by Gluekit

GETTY IMAGES; SCREEN: IEEE

IEEE SERVICES

Resources for Tech Workers Coping With Job Loss

Assistance includes help with networking, continuing education, and résumé writing

BY KATHY PRETZ

TO HELP IEEE members cope with losing a job, *The Institute* asked Chenyang Xu for advice. The IEEE Fellow is president and cochairman of Perception Vision Medical Technologies, known as PVmed. The global startup, which is involved with AI-powered precision radiotherapy and surgery for treating cancer, is headquartered in Guangzhou, China. Xu was formerly general manager of the Siemens Technology to Business North America.

Included with his advice are ways IEEE can help.

Help for unemployed members

Although Xu isn't a financial advisor, he says do what it takes to make sure you have enough money to support yourself and your family until you land your next job.

To help unemployed members keep costs down, IEEE offers a reduced-dues program. For those who have lost their insurance coverage, the organization offers group insurance plans.

Improve your skills

Once you've figured out what your long-range career plan is, you most likely will need to learn new skills, Xu says. If you've decided to change fields, you'll need to learn even more.

IEEE offers online courses that cover 16 subjects including aerospace, computing, power and energy, and transportation. The emerging technologies course offerings cover augmented reality, blockchain technology, virtual reality, and more.

Several leadership courses can teach you how to manage people. They include An Introduction to Leadership, Communication and Presentation Skills, and Technical Writing for Scientists and Engineers.

Finding jobs and consulting gigs

The IEEE Job Site lists hundreds of openings. Job seekers can upload their résumé and set up an alert to be notified of jobs matching their criteria. The site's career-planning portal offers services such as interview tips and help with writing résumés and cover letters.

IEEE-USA offers several on-demand job-search webinars. They cover topics such as how to find the right job, résumé trends, and healthy financial habits.

To earn some extra money, consider becoming a consultant, Xu says.

"Consulting can be an excellent bridge to bring in income while working to secure the next job when facing the situation that your job search may take months or longer," he says.

IEEE-USA's consultants web page offers a number of services. Members can find an assignment by registering their name in the IEEE-USA Consultant Finder. Those who want to network with other consultants can use the site to search for them by state or by IEEE's U.S. geographic regions. The website also offers resources such as e-books, newsletters, and webinars.

To determine how much to charge a client, the IEEE-USA Salary Service provides information from IEEE's U.S. members about their compensation and other details.

IEEE Collabratec's Consultants Exchange offers networking workshops, educational webinars, and more.

If you are financially able and have the right ideas and expertise, Xu says, another option might be to launch your own company.

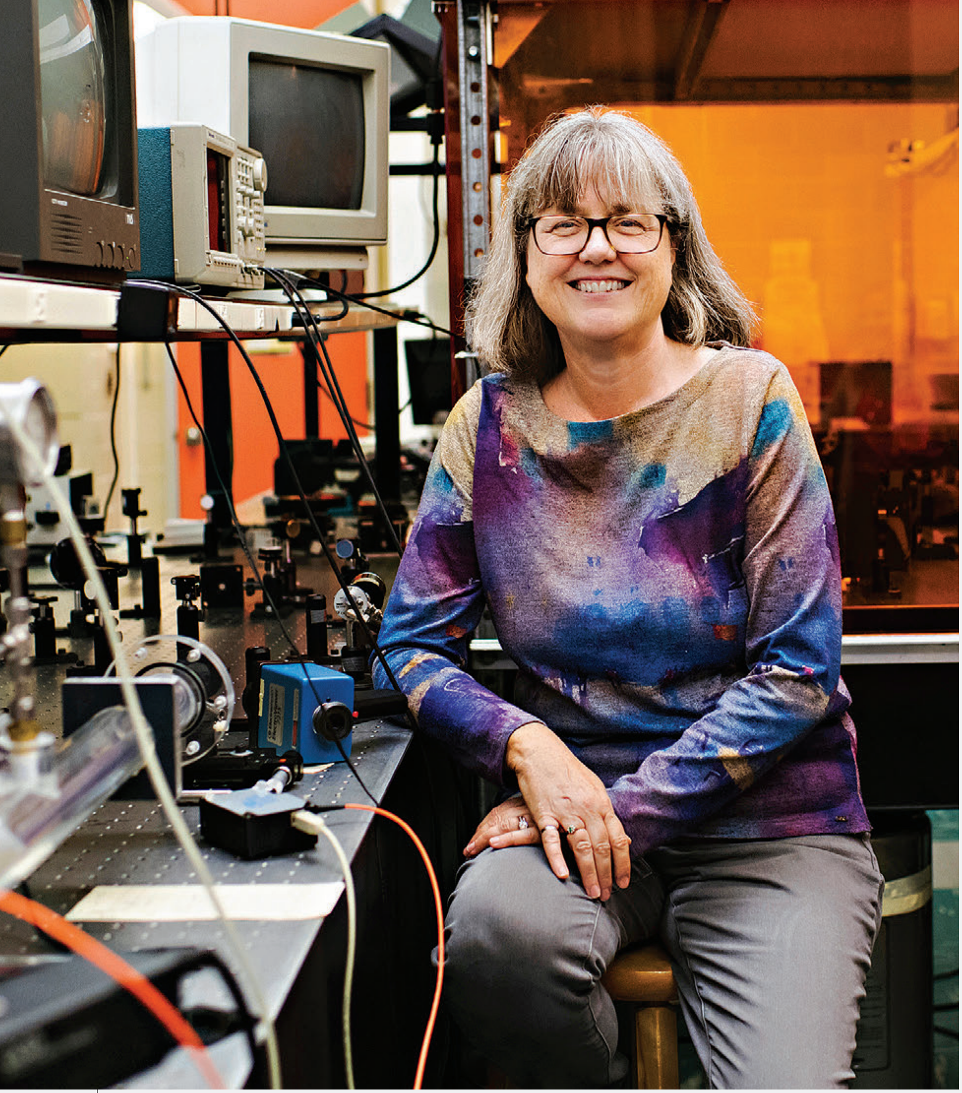
The IEEE Entrepreneurship program offers a variety of resources for founders. Its IEEE Entrepreneurship Exchange is a community of tech startups, investors, and venture capital organizations that discuss and develop entrepreneurial ideas and endeavors. There's also a mentorship program, in which founders can get advice from an experienced entrepreneur.

Networking and social media

Don't overlook the power of networking in finding a job, Xu advises.

You're likely to meet people who could help you at your IEEE chapter or section meetings and at IEEE conferences, Xu says.

"You will be surprised about how many contacts you can meet who might help you find a job, mentor you, or give you information about a company that might be hiring," he says. ■



Honorary Member Donna Strickland in a lab at the University of Waterloo in Ont., Canada, where she teaches physics.

UNIVERSITY OF WATERLOO

PROFILE

Donna Strickland's Tech Is Used in Lasik

The Nobel Laureate's technique paved the way for high-intensity lasers

BY JOANNA GOODRICH

GROWING UP, Donna Strickland had one goal in mind: Earn a Ph.D. But she didn't know what subject she wanted to pursue until she took a course on lasers during her undergraduate studies in physics at McMaster University, in Hamilton, Ont., Canada.

Lasers seemed "really cool—like something from a science-fiction novel," Strickland says. Little did she know that her newfound passion would one day earn her a Nobel Prize in physics.

While conducting research in optics for her doctorate at the University of Rochester, in New York, Strickland worked with French physicist Gérard Mourou, a laser pioneer. Together, while experimenting with how to increase a laser's peak power without damaging it, they invented the chirped-pulse amplification technique. CPA, which produces short laser pulses that reach high intensity, now is used in corrective eye surgery, medical imaging, smartphone manufacturing, and more.

Strickland and Mourou shared the 2018 Nobel Prize in physics with IEEE Life Fellow Arthur Ashkin, who invented a separate technology: "optical tweezers," which use low-power laser beams to manipulate living cells and other tiny objects.

Her invention also earned her the 2023 IEEE Honorary Membership, which is sponsored by IEEE.

Strickland is a physics professor at the University of Waterloo, in Ontario, where she leads a group of researchers that is developing high-intensity laser systems for nonlinear optics investigations such as generating midinfrared pulses by difference frequency mixing and studying the multifrequency Raman generation technique.

High-intensity lasers

After graduating in 1981 with a bachelor's of engineering degree in physics from McMaster, Strickland moved to New York to pursue a doctorate in optics at the University of Rochester. She joined Mourou at the university's Laboratory for Laser Energetics, where he was looking for ways to increase lasers' intensity (their optical power) without damaging the devices.

Pulsed lasers can concentrate light onto a small area for a short time to produce power. Peak intensities increased rapidly for several years after physicist Theodore Maiman demonstrated the first laser in 1960. But the intensities plateaued for more than a decade after 1970 because amplifying the light past a certain point damaged the laser.

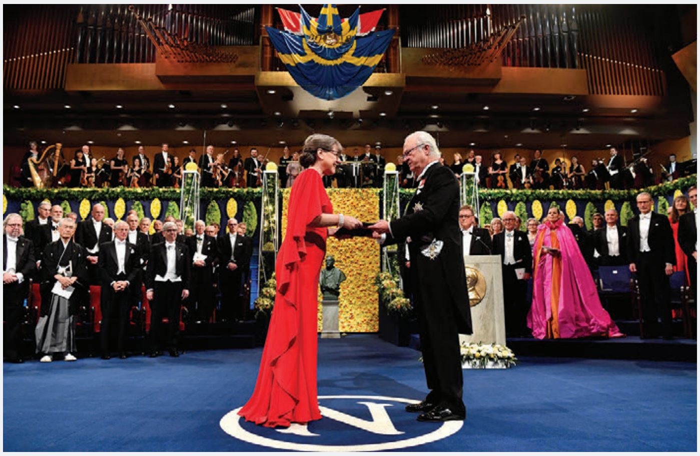
In his research on how light interacts with matter, Mourou hypothesized in 1983 that spacing out and augmenting pulses before bringing them back together could result in higher-intensity laser pulses without damage. But he didn't know how to accomplish it, Strickland says. So for her doctoral research, she tested his hypothesis with different laser systems. None of her experiments worked, however.

Strickland and Mourou found the solution when attending the 1984 International Conference on Ultrafast Phenomena. The biannual event brings together scientists who study processes in atoms, molecules, or materials that occur in millionths of a billionth of a second or faster.

Both attended a presentation at the conference about the newly developed optical fiber pulse compression of neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers. With the technique, 100-picosecond pulses could be compressed to 1 ps using nonlinear optics in an optical fiber to increase a laser's spectral bandwidth. It was found that compression was most successful when the pulses were allowed to stretch through dispersion in the fiber.

Employer University of Waterloo, in Ontario
Title Physics professor
Alma mater University of Rochester, in New York

She and Mourou figured out that the pulse needed to be stretched before it was amplified rather than afterward, as what had been done. Stretching the pulse meant it could be recompressed to produce the desired intensity.



Donna Strickland receives the 2018 Nobel Prize in physics from King Carl Gustaf of Sweden, at the Stockholm Concert Hall.

HENRIK MONTGOMERY/TT NEWS AGENCY/GETTY IMAGES

To test their theory, the two built a system at the Laboratory for Laser Energetics, which was composed of a 2-watt Nd:YAG laser, 1.4 kilometers of optical fiber, an amplifier, and a pair of parallel gratings.

The Nd:YAG laser pumped a short pulse at 100 ps into the optical fiber. As the velocity of light is dependent on wavelength, the red component of the light propagates faster than the blue within the fiber.

That is referred to as a "chirped pulse," Strickland says, because a bird's chirp has a similar frequency structure.

The chirped pulse makes the duration of the pulse longer and spreads out the intensity so that it doesn't damage the laser. The stretched, lower-energy density pulse was then amplified and passed through a pair of parallel diffraction gratings—which allowed the trailing blue component to catch up to the red. Both were reassembled by reflecting off the gratings. The reassembled pulse was three times more powerful than the original one, Stickland says.

The technique has since paved the way for the shortest and most intense laser pulses ever created, making it possible to build more compact and precise laser systems.

From Princeton to Waterloo

After helping develop CPA, in 1988 Strickland became physicist Paul Corkum's second postdoctoral research fellow. Corkum, who worked for the Canadian National Research Council, specialized in laser science and pioneered the development of attosecond physics.

After three years, in 1991 she became a physicist at the Lawrence Livermore National Laboratory, a U.S. Department of Energy facility in California.

Strickland left in 1992 to join the technical staff at Princeton's Advanced Technology Center for Photonics and Opto-electronic Materials.

She returned to Canada in 1996 to join the University of Waterloo's physics department as an assistant professor. She was promoted to associate professor in 2002. From 2007 to 2013, she served as associate chair of the department.

"When I was young, I just wanted to get a Ph.D. and stay in school," Strickland says. "Being a professor is the next best thing to being a student." ■

> "When I was young, I just wanted to get a Ph.D. and stay in school. Being a professor is the next best thing to being a student."

HISTORY

The CT Scanner Was Invented by a Music Company Engineer

Like putting the brain "through a bacon slicer," the inventor said

BY JOANNA GOODRICH

THE INSPIRATION FOR computed tomography (CT) came from a chance conversation that research engineer Godfrey Hounsfield had with a doctor while on vacation in the 1960s. The physician complained that X-ray images of the brain were too grainy and only two-dimensional.

Hounsfield worked at Electrical and Musical Industries in Hayes, England. Probably best known for producing and selling Beatles records, EMI also developed electronic equipment.

When Hounsfield returned to work after that vacation, he wanted to develop a machine that could create three-dimensional brain images. The machine would project narrow beams of X-rays through a person's head, and a computer would use the resulting data to construct a series of cross-sections that together would represent the brain in 3D.

Hounsfield worked with neuroradiologists to build the machine, and in 1971 they produced the first computed tomography scan of a human brain. CT scans are now used to pinpoint the location of blood clots, tumors, and bone fractures.

For his invention, Hounsfield was named corecipient of the 1979 Nobel Prize in physiology or medicine.

Hounsfield's scanner was recently commemorated with an IEEE Milestone during a ceremony held at the EMI Old Vinyl Factory, in Hayes, England, where the technology was developed. The IEEE United Kingdom and Ireland Section sponsored the nomination.

Music and medical equipment

After the X-ray machine was invented in 1896, it quickly became standard equipment in hospitals. The machine produces great images of bones because their dense structures absorb X-ray beams well, which makes the bones look white on film. But soft-tissue organs such as the brain looked foggy because the radiation passed through them.

While Hounsfield served with the Royal Air Force, he learned the basics of electronics and radar. In 1951 he joined EMI, where he developed guided weapon systems and radar. His interest in computers grew, and in 1958 he helped design the Emidec 1100—the first commercially available all-transistor computer made in Britain.

After that project, Hounsfield's supervisor warned him that his job would be in jeopardy if he didn't come up with another good idea.

Hounsfield thought back to the conversation with the doctor about the limitations of X-ray images, then he proposed the project that would become the CT scanner.

EMI didn't develop or manufacture medical equipment and wasn't interested in getting into that line of business, but Hounsfield's supervisor believed in his idea and approved it. The company couldn't fully fund the project, so Hounsfield applied for and received a grant of around US $40,000—approximately $300,000 in 2023 figures—from the British Department of Health and Social Care.

Cow brains and human ones

Hounsfield worked with neuroradiologists James Ambrose and Louis Kreel to build the first prototype. It was small enough to sit atop a table. They tested the machine on small pigs, and after successfully producing images of their brains, the three built a full-size scanner.

The CT scanner was first tested on human brains preserved in formalin. But the brains weren't ideal because the chemical had hardened their tissues so severely that they no longer resembled normal brain matter, as described in an article about the scanner in *The Jewish News of Northern California*. Because the scanner was intended for use on living patients, Hounsfield and his team looked for a brain similar to a human's.

Research engineer Godfrey Hounsfield invented the CT scanner to create three-dimensional brain images.

PA IMAGES/GETTY IMAGES

They procured fresh cow brains, but those couldn't be used because an electric shock was used to stun the animals before they were slaughtered. The procedure caused the brain to fill with blood, and the fluid obstructed the radiologists' view of the organ's structure.

Ambrose suggested using kosher cow brains because instead of being stunned, the animals had their jugular slit. The process drained blood away from the skull—which enabled clear CT scans of the brain.

After several successful tests, the machine was ready to be tried on a human. The scanner was installed in 1971 at Atkinson Morley Hospital, in London, where Ambrose worked. The first patient was a woman who showed signs of a brain tumor.

She lay on a table as X-rays were shot through her skull from a single site above her head. The beams passed through her and struck a crystal detector housed in the gantry below her head. Both the X-ray source and the detector moved around her in 1-degree increments until they had turned 180 degrees, with each device ending up at the other one's starting point.

That allowed the scanner to depict the brain in individual layers. Hounsfield described it as putting the brain "through a bacon slicer," according to an article about the scanner on the Siemens MedMuseum website.

The detector recorded the X-ray signals and sent the data to a computer. The computer constructed an image of the brain using physicist Allan MacLeod Cormack's algebraic reconstruction technique. The technique built up an image by filling in a matrix, each square of which corresponded to a part of the examined organ, according to a Nobel news release about the scanner. Because the crystal detector was 100 times more sensitive than X-ray film, the density resolution was much higher, making the resulting image much clearer.

It took almost three hours for an image to be constructed. It showed a cystic mass about the size of a plum on the patient's left frontal lobe.

EMI began manufacturing CT scanners and sold them to hospitals. But within five years, General Electric, Siemens, and other companies began making more enhanced, full-body scanners. EMI eventually stopped producing its scanners because it couldn't compete with the other manufacturers.

Cormack shared the 1979 Nobel Prize with Hounsfield.

Administered by the IEEE History Center and supported by donors, the Milestone program recognizes outstanding technical developments around the world. ■

Thanks to donations made to the IEEE Smart Village program, IEEE Senior Member Chief Tunde Salihu [third from left] and his employees were able to install a microgrid at a medical facility in Illorin, Kwara, Nigeria.

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NEWS

IEEE Foundation Celebrates 50 Years of Philanthropy

BY KATHY PRETZ

SINCE ITS LAUNCH in 1973, the IEEE Foundation has raised more than US $135 million for more than 250 IEEE programs that improve access to technology, enhance technological literacy, and support education.

IEEE's philanthropic partner is celebrating its 50th anniversary with several events that showcase the profound impact donors around the world have made. It also has introduced new ways to recognize its donors and has added a focus area where contributions will be directed.

"The global need for sustainable development, Internet access, STEM education, and inspiring a new, diverse generation of technologists to take up such worthy endeavors has never been greater," said Ralph Ford, the Foundation's president. "Generous donors and members are the lifeblood fueling the IEEE Foundation's world-changing initiatives, which have positively impacted thousands of communities."

The celebrations kicked off in February with an event held at the Sheraton New York hotel in Times Square. Actors posing as engineering pioneers Marie Curie, Thomas Alva Edison, Lewis Latimer, Nikola Tesla, and George Westinghouse talked about how the technologists' inventions changed the world.

The anniversary of the Foundation, which initially was established to accept and manage donations in support of the IEEE Awards Program, was highlighted throughout the IEEE Vision, Innovation, and Challenges Summit and Honors Ceremony, held in May.

The Foundation also sponsored the IEEE Sections Congress, held in August in Ottawa and hosted several events there.

In addition, the Foundation added six giving levels to the IEEE Heritage Circle, a cumulative-giving donor-recognition program that has named various giving levels for innovators in the fields of science and technology.

It also added a fifth area, or pillar, to help guide the philanthropic focus. The other four pillars are designated *illuminate*, *educate*, *engage*, and *energize*.

These are the current programs that are supported by generous donors:

IEEE History Center
IEEE Life Members Fund
IEEE Women in Engineering
IEEE TryEngineering
IEEE Smart Village
IEEE-Eta Kappa Nu
IEEE SIGHT

To make a donation to the IEEE Foundation, visit its website: ieeefoundation.org

IEEE TryEngineering Program by the Numbers

IEEE TRYENGINEERING PROVIDES educators, preuniversity students, and volunteers with activities, lesson plans, and resources to help engage and inspire the next generation of science, technology, engineering, and mathematics professionals.

It achieves its goal through TryEngineering.org and virtual and in-person events including the annual IEEE STEM Summit. IEEE TryEngineering also provides grants for education programs created by volunteers.

Here is a look at IEEE TryEngineering's progress since 2021.

1,566

in-person volunteer-led events have been held

129,000

students engaged in volunteer-led events

20,360

teachers engaged in volunteer-led events

91

grants totaling US $116,000 have been awarded

944

people attended the 2022 IEEE STEM Summit

Top 10 countries with the most TryEngineering.org visitors:

1 United States
2 China
3 India
4 Philippines
5 Malaysia
6 Cambodia
7 Thailand
8 South Africa
9 Georgia
10 Sri Lanka

SOURCE: IEEE Educational Activities

The food-delivery robot was deployed last year at three airports, including this one in Pittsburgh.

OTTONOMY

STARTUP

Ottobot Delivers at the Airport

It can navigate indoor spaces where GPS can't penetrate, making autonomous deliveries possible

BY JOANNA GOODRICH

THE NEXT TIME you're taking a trip, an autonomous robot might deliver food from an airport restaurant to your gate.

The idea for Ottobot, a delivery robot, came out of a desire to help restaurants meet the increased demand for takeout orders during the COVID-19 pandemic. Ottobot can find its way around indoor spaces where GPS can't penetrate.

The robot is the brainchild of Ritukar Vijay, Ashish Gupta, Pradyot Korupolu, and Hardik Sharma. The four founded Ottonomy in 2020 in Santa Monica, Calif. The startup now has more than 40 employees in the United States and India.

Ottobot was deployed in 2022 at the Cincinnati/Northern Kentucky, Rome, and Pittsburgh airports. It is expected to be used by restaurants, grocery stores, and postal services in Europe and North America this year.

Vijay and his colleagues say they focused on three qualities: full autonomy, ease of maneuverability, and accessibility.

"The robot is not replacing any staff members; it's aiding them in their duties," Vijay says. "It's rewarding seeing staff members at our pilot locations so happy about having the robot helping them do their tasks. It's also very rewarding seeing people take their delivery order from the Ottobot."

Autonomous technology

For 15 years Vijay, an IEEE senior member, worked on autonomous robots and vehicles at companies including HCL Technologies, Tata Consultancy Services, and THRSL. In 2019 he joined Aptiv, an automotive technology supplier headquartered in Dublin. There he worked on BMW's urban mobility project, which is developing autonomous transportation and traffic-control systems.

He noticed that Aptiv and its competitors were focusing more on building electric cars rather than autonomous ones. He figured it was going to take a long time for autonomous cars to become mainstream, so he began to look for niche applications. He hit upon restaurants and other businesses that were struggling to keep up with deliveries.

Ottobot reduces delivery costs by up to 70 percent, Vijay says, and it can reduce carbon emissions for small-distance deliveries almost 40 percent.

Airport assistant

Within the first few months of the startup's launch, Vijay and the Ottonomy team began working with the Cincinnati/Northern Kentucky Airport. The facility wanted to give passengers the option of having food from the airport's restaurants and convenience stores delivered to their gate, but it couldn't find an autonomous robot that could navigate the crowded facility without GPS access, Vijay says.

To substitute for GPS, the robot used 3D lidars, cameras, and ultrasonic sensors. The lidars provide geometric information about the environment. The cameras collect semantic and depth data, and the short-range ultrasonic sensors ensure that the Ottobot detects poles and other obstructions. The Ottonomy team wrote its own software to enable the robot to create high-information maps—a 3D digital twin of the facility.

Vijay says there's a safety mechanism in place that lets a staff member "take over the controls if the robot can't decide how to maneuver on its own, such as through a crowd." The mechanism also notifies an Ottonomy engineer if the robot's battery power is running low, Vijay says.

"Imagine passengers are boarding their plane at a gate," he says. "Those areas get very crowded. During the robot's development process, one of our engineers joked around, saying that the only way to navigate a crowd of this size was to move sideways. We laughed at it then, but three weeks later we started developing a way for the robot to walk sideways."

All four of Ottobot's wheels are powered and can steer simultaneously—which allows it to move laterally, swerve, and take zero-radius turns.

The technology also allows Ottobot to maneuver outside an airport setting. The wheels can carry the robot over sidewalk curbs and other obstacles.

Founded 2020
Headquarters
Santa Monica, Calif.
Founders
Ritukar Vijay, Ashish Gupta, Pradyot Korupolu, and Hardik Sharma

"It's rewarding seeing staff members at our pilot locations so happy about having the robot helping them do their tasks."

Ottobot can adjust its position and height so that anyone—including children, the elderly, and people with disabilities—can reach its cargo.

OTTONOMY

Ottobot is 1.5 meters tall—enough to make it visible. It can adjust its position and height so that its cargo can be reached by children, the elderly, and people with disabilities, Vijay says.

The robot's compartments can hold products of different sizes, and they are large enough to allow it to make multiple deliveries in a single run.

To place orders, customers scan a QR code at the entrance of a business or at their gate to access Crave, a food ordering and delivery mobile app. After placing their order, customers provide their location. In an airport, the location would be the gate number. The customers then are sent a QR code that matches them to their order.

A store or restaurant employee loads the ordered items into Ottobot. The robot's location and estimated arrival time are updated continuously on the app.

Delivery time and pricing varies by location, but on average retail orders can be delivered in as quickly as 10 minutes, while the delivery time for restaurant orders generally ranges from 20 to 25 minutes, Vijay says.

Once the robot reaches its final destination, it sends an alert to the customer's phone. Ottobot then scans the person's QR code, which unlocks the compartment.

IEEE membership is vital

Being an IEEE member has given Vijay the opportunity to interact with other practicing engineers, he says.

"When my team and I were facing difficulties during the development of the Ottonomy robot," he adds, "I was able to reach out to the IEEE members I'm connected with for help."

Access to IEEE publications such as *IEEE Robotics and Automation Magazine, IEEE Robotics and Automation Letters,* and *IEEE Transactions on Automation Science and Engineering* has been vital to his success, he says. His team referred to the journals throughout Ottobot's development and cited them in their technical papers and when completing their patent applications.

"Being an IEEE member, for me, is a no-brainer," Vijay says. ■

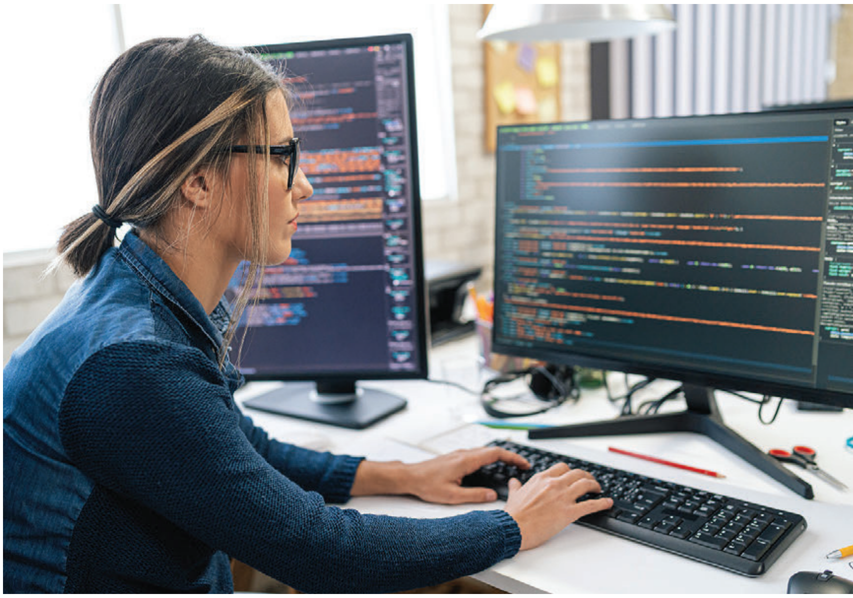
IEEE Spectrum

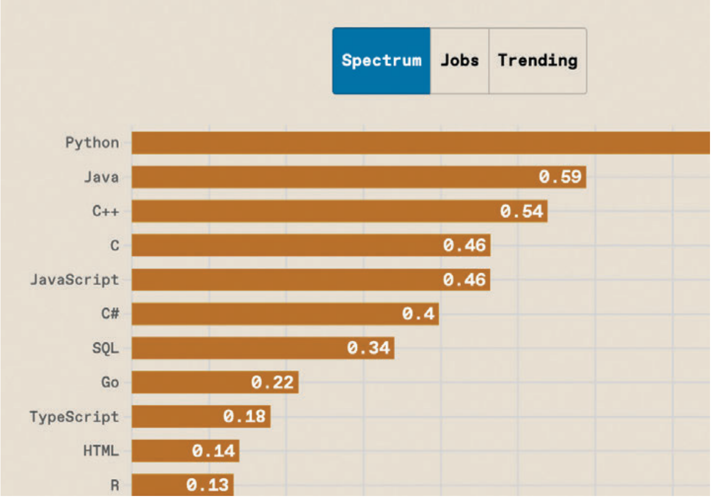
Top Programming Languages 2023

Now Online

Get our latest rankings of what's hot and what's not in software development

What computer languages do programmers love or employers demand? For the 10th year, *IEEE Spectrum's* interactive rankings identify what are the must-know languages for developers through mining and combining data from around the world.





Deep Analysis

We look at the relative popularity of dozens of languages, so that specialized languages like R, VHDL, and even Cobol are not overlooked, and you can see the big picture.

Data You Can Trust

We gather data from sources such as the IEEE *Xplore* digital library, IEEE Job Site, Stack Overflow, Google, and more to create combined rankings that are more than the sum of their parts.

⟵ **Scan the QR code** or go to **Spectrum.ieee.org/top-programming-languages-2023** now to find out which programming languages are in high demand, improve your skills, and further your career!

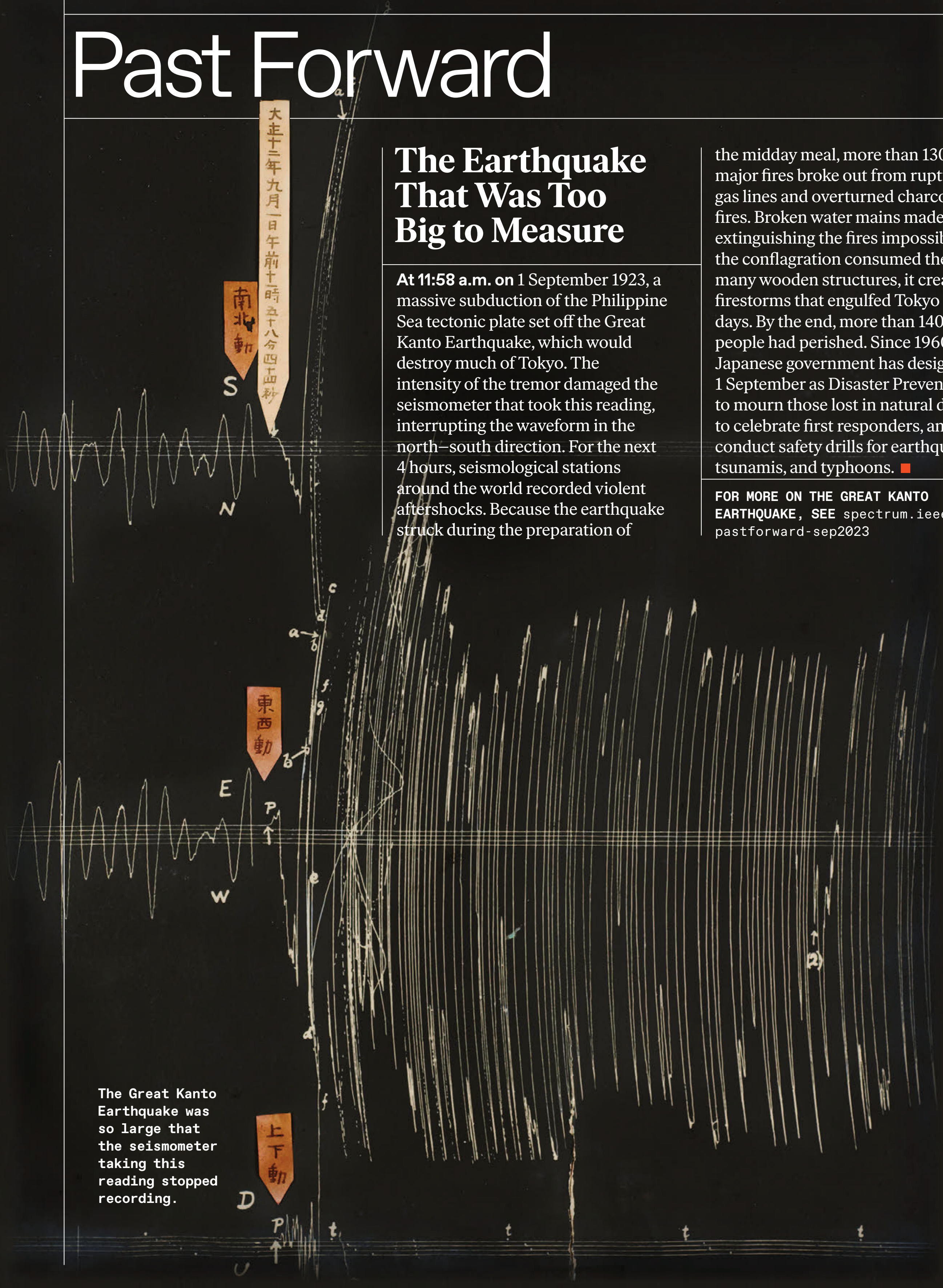
BY ALLISON MARSH

Past Forward

The Earthquake That Was Too Big to Measure

At 11:58 a.m. on 1 September 1923, a massive subduction of the Philippine Sea tectonic plate set off the Great Kanto Earthquake, which would destroy much of Tokyo. The intensity of the tremor damaged the seismometer that took this reading, interrupting the waveform in the north–south direction. For the next 4 hours, seismological stations around the world recorded violent aftershocks. Because the earthquake struck during the preparation of the midday meal, more than 130 major fires broke out from ruptured gas lines and overturned charcoal fires. Broken water mains made extinguishing the fires impossible. As the conflagration consumed the city's many wooden structures, it created firestorms that engulfed Tokyo for two days. By the end, more than 140,000 people had perished. Since 1960, the Japanese government has designated 1 September as Disaster Prevention Day to mourn those lost in natural disasters, to celebrate first responders, and to conduct safety drills for earthquakes, tsunamis, and typhoons. ■

FOR MORE ON THE GREAT KANTO EARTHQUAKE, SEE spectrum.ieee.org/pastforward-sep2023



The Great Kanto Earthquake was so large the seismometer taking this reading stopped recording.

GREAT KANTO EARTHQUAKE MEMORIAL MUSEUM