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FOR THE TECHNOLOGY INSIDER

JANUARY 2023

IEEE Spectrum

Top Tech 2023

Green Hydrogen Gets Real Down Under

IEEE

Dr. Natalia Ares, University of Oxford

Reaching New Heights Together!

Congratulations to the group of Natalia Ares at the University of Oxford and their collaborators on demonstrating an all-RF reflectometry quantum device tuning using a machine learning algorithm. The algorithm can tune a double quantum dot in just a few minutes without prior knowledge about the device configuration. This achievement paves the way to more scalable quantum device architectures.

We are excited to help the whole team drive the field forward with innovative approaches to quantum measurements using Zurich Instruments lock-in amplifiers.

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LTA RESEARCH

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ON THE COVER:
Illustration by Carl De Torres

TOP: AST SPACEMOBILE; BOTTOM: WORLDCOIN

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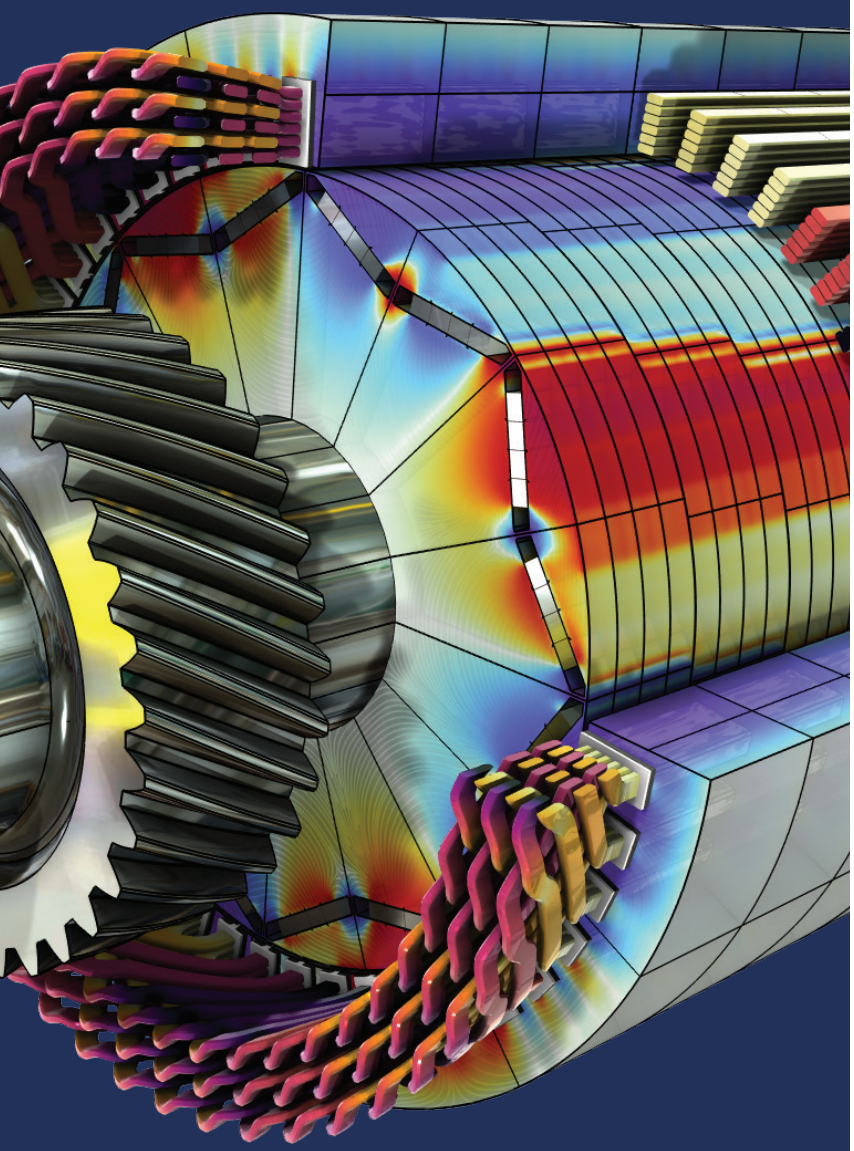

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Looking Back to See Ahead

Technologies decades in the making finally get their star turn in 2023

Magazines love to dabble in prognostication, particularly when it comes to emerging technology. Startups show such futuristic pronouncements to potential investors, who in turn use them as data points to inform their bets. And as readers, we gravitate toward them, if only so we can feel superior when, say, a highly anticipated product launch bombs—chef's kiss to Mark Zuckerberg for the schadenfreude fest that is the metaverse.

Think of *IEEE Spectrum*'s annual technology forecast as prognostication filtered through a skeptical lens and years of ongoing coverage of technological advances from lab to market. Each January, we look at projects across the globe and from a range of engineering disciplines that will have major milestones in the coming year. While some technologies flop and fade away, others produce multiple hype cycles that raise and then dash hopes again and again. Take flying cars. Back in 2007, we predicted that the flying-car startup Terrafugia would fail. The company lurched along for years until finally ceasing U.S. operations in 2021, ironically just after receiving a Special Light-Sport Aircraft airworthiness certificate from the U.S. Federal Aviation Administration.

But as we wrote in 2014, flying cars are an idea that will not die. And even though the road—or the flight path—to commercial success is riddled with regulatory and social obstacles, eVTOLs (a newer and less sullied acronym-a-licious moniker for flying cars) have attracted billions of dollars in investment in recent years. And now, the sector seems poised to finally take off, as Editorial Director of Content Development Glenn Zorpette reports in his story about Opener's BlackFly eVTOL [p. 32].

Flying cars illustrate one path that emerging technologies follow, with innovators and investors taking chances and failing early on. True believers learn from those failures, ultimately leading to solutions that are then brought to market.

Sometimes, though, externalities like a changing climate fast-track technologies that have been languishing in development for decades. Back in 2001, Senior Editor Michael J. Riezenman wrote about hydrogen fuel cells as a promising answer to long-haul transportation needs. Back then, the hydrogen economy seemed right around the corner. Fast-forward 22 years and Contributing Editor Peter Fairley reports on two Australian companies that aim to use hydrogen to make a big dent in the country's greenhouse-gas emissions [p. 24]. One company is using renewable energy to produce hydrogen as fuel for huge trucks to haul zinc ore. The other is developing a new generation of electrolyzers to produce hydrogen for export, although exactly how that will work has yet to be determined. Thank the pressures of the climate crisis for this green-hydrogen boom.

In January 2001, we wrote about hydrogen-EV hybrids [top]; 2007 was the year we touted the now-defunct Terrafugia electric plane [center]; and 2013 was the (one) year of Google Glass [bottom].

Cryptocurrencies, which we've been covering since they emerged, have imploded over the last several months. This crypto winter has soured many people on that particular application of blockchain technology, but there are many other, perhaps more promising ways to apply a blockchain. One is as a means of providing proof of personhood, as the journalist Edd Gent explores in his critical look at Worldcoin [p. 42]. The company's founders want Worldcoin to be not only a global currency that will somehow redistribute wealth via universal basic income but also a secure means of biometric identification, with a dose of buzzy, Web3 facilitation thrown in for good measure. And so, while crypto is tanking and the NFT market has fizzled, something useful may yet rise from the ashes of Web3. I'll go out on a limb here and predict that Web3 will be recalled in years to come as a figment of some collective pandemic fever dream.

Check back in a few years to see how that prognostication pans out. Meanwhile, have some fun with this issue and with your exclusive member benefit: online access to our feature archives from 2000 to 2020. Log in to the *Spectrum* website to trace how technologies like lidar and microLEDs have developed into components that now enable other technologies—a new generation of blimps [p. 28] and optical interconnects for chiplets [p. 30], respectively—which are also featured in this issue. ■

PORTRAIT BY SERGIO ALBIAC

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ELIE DOLGIN

Dolgin is a former scientist and a Massachusetts-based journalist specializing in biomedical research. On page 48, he examines the prospects of new nerve-stimulation implants for treating arthritis and other inflammatory conditions. "The notion that tickling nerves can help quell inflammation is kind of wild," says Dolgin. "The anecdotal evidence is tantalizing, and I'm excited to see if the early promise stands up to greater scrutiny."

EDD GENT

Gent, a freelance journalist based in Bangalore, India, writes about emerging technologies in computing, engineering, energy, and bioscience. In this issue he covers the new cryptocurrency, Worldcoin [p. 42]. Its founders hope Worldcoin might help spread wealth more evenly around the world. The key technology is a biometric-scanning device that looks like a giant eyeball, which they've dubbed the Orb. "It just sounds like something straight out of a dystopian sci-fi film," says Gent.

LUCAS LAURSEN

Laursen is a freelance journalist based in Madrid, covering the role of science and technology in global development. On page 52 of this issue, he writes about the technologies allowing everyday smartphones to connect directly to satellites, eliminating no-coverage zones. Laursen has firsthand experience of those. "A satellite phone once failed on me during a mountaineering expedition in the Borkoldoy Range of Kyrgyzstan," he says. If this technology had been available, he suspects he would've had far more peace of mind on that trip.

CORRECTION: In the illustration on page 23 of "A Bionic Nose to Smell the Roses Again" [November 2022], the labels for the amygdala and the entorhinal cortex and hippocampus pointed to the wrong structures in the brain. We regret the error. See the revised illustration in the online version of the article, https://spectrum.ieee.org/covid-smell-prosthetic.

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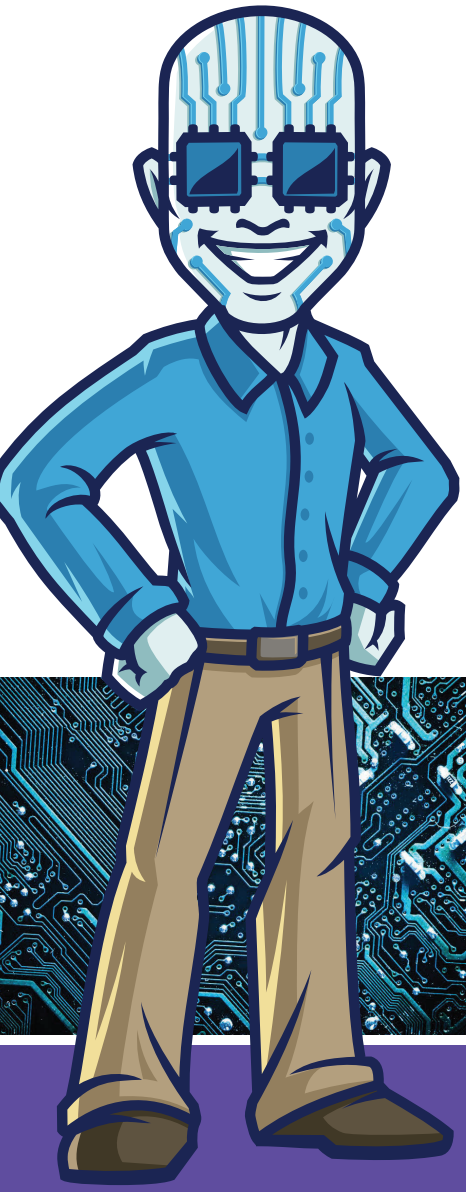

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News

COMPUTER GRAPHICS

AI Is a Powerful Pixel Painter

> With neural rendering, AI beats pixel-by-pixel graphics processing by 530 percent

BY MATTHEW S. SMITH

NVIDIA

On 20 September, Nvidia's vice president of applied deep learning, Bryan Catanzaro, went to Twitter with a bold claim: In certain GPU-heavy games, like *Portal with RTX*, seven out of eight pixels on the screen are generated by a new machine-learning algorithm. That's enough, he said, to speed rendering by 530 percent.

This impressive feat is currently limited to a few dozen 3D games. But it's a hint at the gains that an AI approach to computer-graphics generation, called neural rendering, will soon deliver. Because of its speedups and efficiencies, the technique is poised to unlock new potential in everyday consumer electronics.

The new algorithm is DLSS 3, the latest iteration of Nvidia's Deep Learning Super Sampling image-enhancement technologies. It examines sequential frames for changes between them and can thus interpolate unique, AI-generated frames in the middle of traditionally rendered frames.

The 530 percent speedup is based on a best-case scenario, which references testing by Digital Foundry, a 3D-graphics publication and YouTube channel. But other tests also give impressive results. Most show DLSS 3 delivering a two- to threefold performance gain over purely traditional rendering at 4K resolution. And while Nvidia leads the pack, it has competitors, including Intel's XeSS (Xe Super Sampling), an AI-powered upscaler. AMD's RDNA 3 graphics architecture also includes a pair of AI accelerators in each of the chip's compute units. In AMD's case, however, the company has not made clear how it might use such AI hardware.

Games have led the wave of neural rendering because they pose the right kind of problem—namely, "where you look at little patches of an image and try to guess what's missing," says Jon Barron, senior staff researcher at Google. Similarities between frames, along with a frame rate high enough to obscure minor errors in motion, play to machine learning's strengths.

Nvidia's AI trains on a 2D image to render a 3D scene. The quality of the scene becomes more precise as training proceeds. The images here were adapted from a video demonstrating the rendering capabilities after just 10 seconds of training time.

It's also far from perfect: DLSS 3 has trouble with scene transitions, while XeSS can cause a shimmering effect in some situations. However, both Barron and Catanzaro think such obstacles can be overcome by feeding neural-rendering models additional training data. The coming year provides the chance to see the technology progress as Nvidia, Intel, and AMD work with software partners to enhance their respective neural-rendering techniques.

And this is just the tip of the spear. Barron sees a fork between "2D neural-rendering" techniques like Nvidia DLSS 3, which improves the results of a traditional graphics pipeline, and "3D neural rendering," which generates graphics entirely through machine learning. Barron coauthored a paper on DreamFusion, a machine-learning model that generates 3D objects from plain-text inputs. The resulting 3D models can be exported to rendering software and game engines. Nvidia has shown equally impressive results from Magic3D, a similar generative 3D technique capable of even more detailed 3D models than DreamFusion's.

Anton Kaplanyan, vice president of graphics research at Intel, believes that neural-rendering techniques will make 3D content creation more approachable. "If you look at the current social networks, it's so much commoditized. A person can just click on a button, take a photo, share it with their friends and relatives," says Kaplanyan. "If we want to elevate this experience into 3D, we need to pull people who don't know the professional tools to become content creators as well."

Early results have been impressive, but the technology must still prove itself. "Computer graphics are amazing, it works really well, and we have really good ways of solving a lot of problems that may be the way we do it forever," says Barron. He notes that content creators and developers are already familiar with the tools used to create for, and optimize, a traditional graphics pipeline.

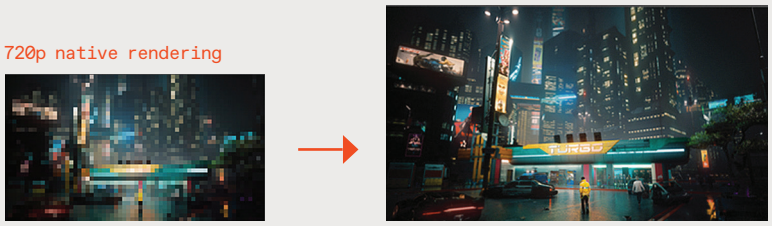
The question, then, is how quickly the graphics industry will embrace 3D neural rendering as an alternative to tried-and-true methods. It may prove an unsettling transition because of the conflicting incentives that surround it. Machine-learning models often run well on modern graphics architectures, but there's tension in how GPU, CPU, and dedicated AI coprocessors—all of which are relevant to AI performance, depending on its implementation—combine in a consumer product. Betting on the wrong

Three examples of neural-rendering techniques

Upscaling

720p native rendering

4K upgrade



Frame insertion

Text-to-3D

Neural-rendering techniques include AI upscaling (in which the neural net smartly interpolates between sparse sets of pixels in an ultrahigh-resolution field), AI frame insertion (in which the neural net generates an entire interpolated frame between existing video frames), and text-to-3D (in which a machine-learning language model generates a 3D image model based on a text prompt).

technique, or the wrong architecture to support it, could prove a costly mistake.

Still, Catanzaro believes the lure of 3D neural rendering will be hard to resist. "I think that we're going to see a lot of neural-rendering techniques that are even more radical," he says, referring to generative text-to-image and text-to-3D techniques. "The graphical quality from some of these completely neural models is quite extraordinary. Some of them are able to do shadows and refractions and reflections and these things that we typically only know how to do in graphics with ray tracing....So I would consider those even more radical approaches to neural rendering than DLSS, and I think the future of graphics is going to use both of those things."

Neural rendering is alluring not just for its potential performance but also its potential efficiency. The 530 percent gain DLSS 3 delivers in *Portal* can improve frame rates—or it can lower power consumption by capping the frame rate at a target.

That's a big deal, because consumer electronics has a power-consumption problem. "Moore's Law is running out of steam, as you know, and my personal belief is that post-Moore graphics is neural graphics," says Catanzaro. For Nvidia, neural rendering represents a way to keep delivering big gains without doubling up on transistors.

Intel's Kaplanyan disputes the demise of Moore's Law (Intel CEO Patrick Gelsinger insists it's alive and well), but he agrees that neural rendering can improve efficiency. "There are some solutions to chip size—there are the chiplets, which Pat has talked about," he says. "On the other hand, I also agree that we have a great opportunity with machine-learning algorithms to use this energy and this area way more efficiently to produce new visuals."

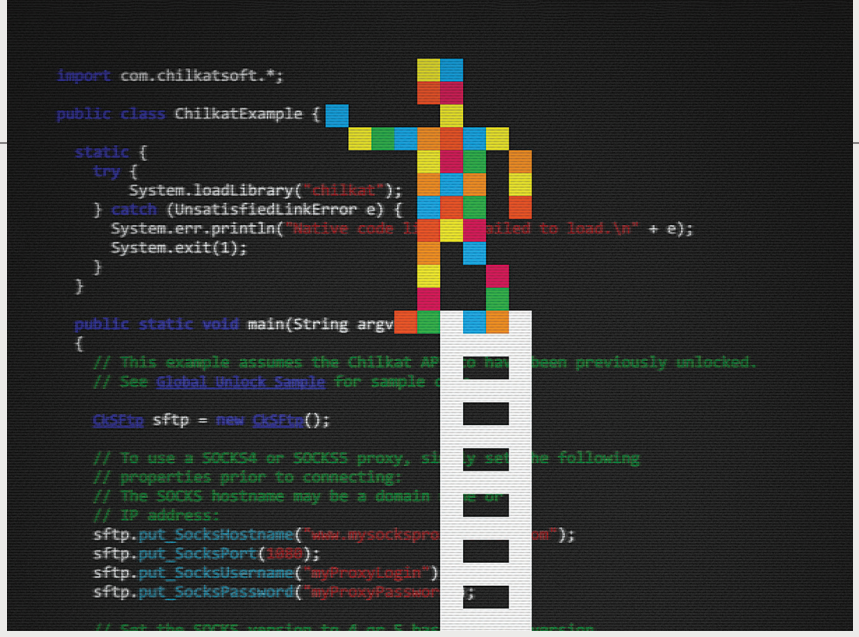
Efficiency is a battleground for AMD, Nvidia, and Intel, as all three companies work with device manufacturers to design new consumer laptops and tablets. For device makers, efficiency gains lead to thinner, lighter devices that last longer on battery, while simultaneously enhancing what users can accomplish with the device.

"I am very excited about enabling the commoditized but very immersive experiences," says Kaplanyan. "Enabling the experiences that you would otherwise see only in high-end Hollywood movies or triple-A games, but also those experiences you would be able to make yourself. You'd be able to do it on your laptop, or some other very power-confined device."

Whichever competitor winds up coming out of this race ahead, 2023 will be a foundational year for neural rendering across the consumer-electronics industry. Nvidia's RTX 40 Series with DLSS 3 support will roll out broadly to consumer desktops and laptops, Intel is expected to expand its Arc graphics line with its upcoming Battlemage architecture, and AMD will launch more variants of cards using its RDNA 3 architecture.

These releases lay the groundwork for a revolution in graphics. It won't happen overnight, and it won't be easy—but as consumers demand ever more impressive visuals, and more capable content creation from smaller, thinner form factors, neural rendering could prove the best way to deliver. ■

NVIDIA



ARTIFICIAL INTELLIGENCE

Do You Own the Code AI Helps You Create? › GitHub Copilot kerfuffle spotlights legal gray area

BY RINA DIANE CABALLAR

GitHub Copilot dubs itself an "AI pair programmer" for software developers, able to automatically suggest code in real time. It's powered by a generative AI model, created by OpenAI and trained on text and source code from publicly available sources.

However, a class-action lawsuit claims that GitHub Copilot; its parent company, Microsoft; and OpenAI have committed open-source software piracy and other violations of open-source licenses. Specifically, the lawsuit states that code generated by Copilot does not include any attribution to the original author of the code, copyright notices, or a copy of the license.

The lawsuit is pioneering in regard to challenging generative AI. But it also raises questions about open-source methods.

"The spirit of open source is not just a space [that] people want to keep open," says Sal Kimmich, an open-source developer advocate at Sonatype, machine-learning engineer, and open-source contributor and maintainer. "We have developed processes in order to keep open source secure, and that requires traceability, observability, and verification. Copilot is obscuring the original provenance of those [code] snippets."

To address the issues with open-source licensing, GitHub plans to introduce a new Copilot feature that will "provide a reference for suggestions that resemble public code on GitHub so that you can make a more informed decision about whether and how to use that code." That feature, says GitHub, includes "providing attribution where appropriate." GitHub also has a configurable filter to block suggestions that match public code.

The onus, however, still falls on developers, as GitHub states in Copilot's terms and conditions: "GitHub does not claim any rights in Suggestions, and you retain ownership of and responsibility for Your Code, including Suggestions you include in Your Code."

Another concern is whether it's legal to train on publicly available code, and whether code generated in that fashion could violate copyright. Kimmich points to the Google *v.* Oracle case, wherein "taking the names of methods, but not the functional implementation, is okay. You're replacing the functional content but still keeping some of the template." In the case of Copilot, it might generate copyrighted code verbatim.

Kit Walsh, a senior staff attorney at the Electronic Frontier Foundation, argues that training Copilot on public repositories is fair use. "Fair use protects analytical uses of copyrighted work. Copilot is ingesting code and creating associations in its own neural net about what tends to follow and appear in what contexts, and that factual analysis of the underlying works is the kind of fair use that cases involving video-game consoles, search engines, and APIs have supported."

Walsh says it boils down to "how much [Copilot] is reproducing from any given element of the training data" and if it encompasses creative expression that is copyrightable. "If so, there could be infringement happening," she says.

The lawsuit is "setting a legal precedent that has implications for other generative tools," Walsh says. "It's the type of work that if a person authored [it, they] could qualify for copyright protection, and it could embody someone else's copyrighted work like snippets of code."

Stella Biderman, an AI researcher at Booz Allen Hamilton and EleutherAI, says she hopes the lawsuit will define what "is actually legal, which is one of the big issues for those working on open-

The lawsuit is "setting a legal precedent that has implications for other generative tools."

—KIT WALSH, ELECTRONIC FRONTIER FOUNDATION

Illustration by Edmon de Haro

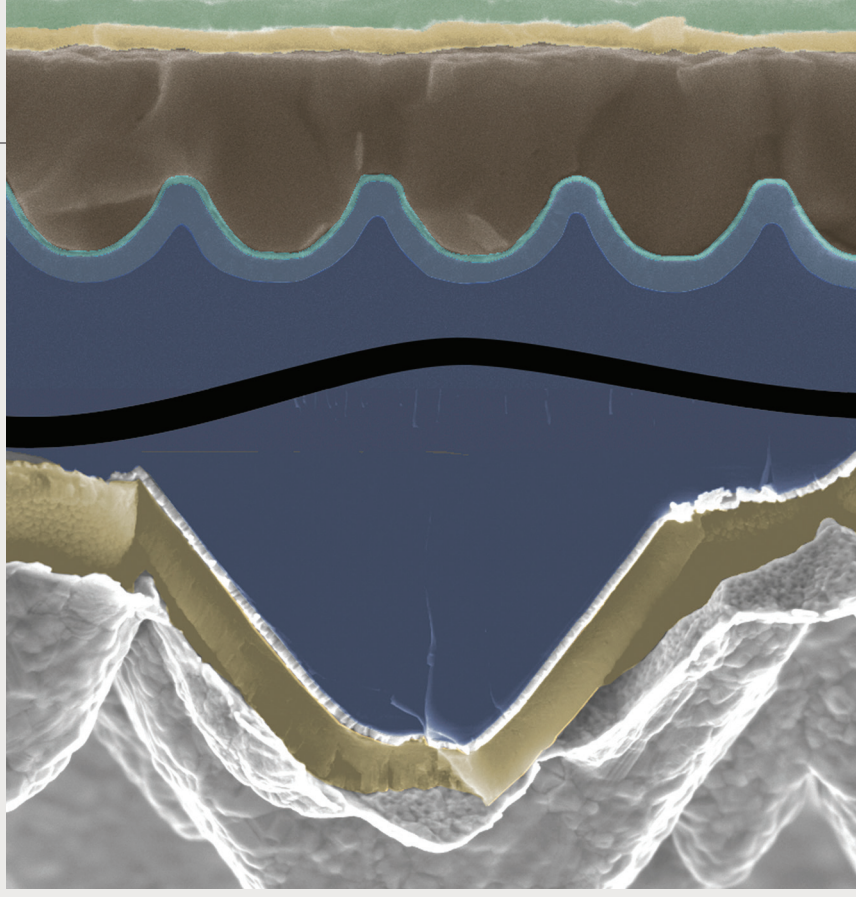
source AI. "I very much hope that what comes out of this lawsuit will be something I can rely on when making decisions about training models in the future."

The open-source community seems divided on the lawsuit and GitHub Copilot itself. For instance, the Software Freedom Conservancy has been vocal about its concerns with Copilot—even calling for a boycott of GitHub—but is cautious about joining the class-action lawsuit. Kimmich says they and other open-source advocates know of open-source developers taking an ethical stance in choosing not to use Copilot, but also others who are enjoying it. "They're learning while developing and executing code on the fly."

Kimmich themself is on a waitlist for Copilot and recognizes the benefits it offers developers. "The neural network behind it is using more than just code to help you—it's providing much more contextual information," they said. "It means I as a developer now have an extended intelligence, which is giving me a contextualized recommendation. I think that's excellent. It's the most powerful generative intelligence that we've had so far for this application."

Yet unless the open-source licensing issue is solved, Kimmich envisions using GitHub Copilot only for pet projects and exploring new packages. "If I as an engineer would like to use Copilot, I will need to be able to restrict what it provides me to code that's attributed to the license or have a license which states that it was codeveloped. If I can't locate the provenance of the original licenses or the original intellectual property, then I need to be able to know if I want to avoid it."

GitHub Copilot might choose to modify its AI model to trace attribution and give credit to the original authors of the code, adding the associated copyright notices and license terms in the process, which Biderman says is technologically feasible. "The position that OpenAI and Microsoft seem to have taken is that it is unduly onerous on them to filter by license when other models successfully do it." She points to academic models such as InCoder as an example, which is trained on code that it has a license for. "There are other options and other models that are both more ethical and more likely to be legal," Biderman says. ■



This image shows perovskite silicon tandem cells in cross section with nanotexture and a back-reflector layer (gold).

P. TOCKHORN/HELMHOLTZ ZENTRUM BERLIN

ENERGY

Perovskite Solar-Cell Efficiency Approaches 30 Percent

Egg-crate-shaped nanostructure boosts photon-to-electron conversion

BY PRACHI PATEL

By adding periodic nanostructures that look like egg-crate foam to tandem solar cells made of silicon and perovskites, researchers at the Helmholtz-Zentrum Berlin, in Germany, have achieved a certified efficiency of 29.8 percent.

This was the world record for tandem solar-cell efficiency until July of this year, when researchers at the Swiss Center for Electronics and the Swiss Federal Institute of Technology Lausanne (EPFL) surpassed it slightly, setting a new record of 31 percent. The German team, however, has presented details of how they achieved their milestone efficiency—and insights about how to further the promise of perovskite solar tech—in a recent paper in *Nature Nanotechnology*.

Silicon solar cells have a theoretical efficiency limit of around 32 percent, with the best cells today reaching efficiencies of just under 27 percent. Solar cells made of III-V semiconductors can achieve efficiencies higher than 30 percent, but those materials are expensive and difficult to process.

Tandem cells, in which silicon is coated with easy-to-make photovoltaic perovskites, offer a way to achieve efficiencies over 40 percent, in theory at least, at low cost and without needing drastically different manufacturing facilities.

Teams working on such tandem devices have so far tried to eke out every little efficiency gain by varying the chemical composition of the perovskites, making nicer, more uniform layers and improving the contact between the two material layers, among other tricks.

The German team, and the Swiss team after them, boosted efficiency by creating a texture on the silicon surface. Texturing solar cells reduces reflection losses, which increases the current that the device generates, says Philipp Tockhorn, a researcher at Helmholtz-Zentrum and first author of the new paper. "Textures are essential to tap the full optical potential of the perovskite–silicon tandem solar cell and to reduce optical losses to a minimum."

The standard way to texture silicon-only cells is to create random pyramidal structures that are several micrometers in size. But that doesn't work for tandem cells, Tockhorn says, because the height of standard pyramidal textures surpasses the thickness of the perovskite layer. To overcome that, researchers have tried to either alter the perovskite deposition method while retaining the pyramid texture, or tweak the pyramidal textures to more easily deposit perovskite solution on them. "There is a challenge to fully cover the texture without pinholes, which would deteriorate the performance," he says.

The Swiss EPFL team's solution was to use a hybrid vapor/solution processing technique that is compatible with pyramidal textured silicon surfaces. They made a 1-square-centimeter solar cell with a power conversion efficiency of 31.25 percent.

But Tockhorn and his colleagues decided to investigate shallower nanotextures. Based on previous experimental work and backed up by optical simulations, the team decided on a sinusoidal design with a hexagonal arrangement. These nanotextures can be easily coated with perovskite without compromising the quality of the perovskite, he says.

The nanotexturing not only improved efficiency, it also increased the yield of high-quality tandem solar cells.

Not only did the nanotexturing improve efficiency, it also increased the yield of high-quality tandem solar cells. That's because the textured surface retained the perovskite solution better than a flat silicon surface, resulting in a better-quality perovskite film. Out of 45 nanotextured tandem solar cells, only two had visible holes after perovskite coating, making for a yield of about 95 percent. The planar devices had a 50 percent yield: Fifteen out of 30 devices showed macroscopic holes.

The German group used ultraviolet nanoimprint lithography and etching to make the nanostructured silicon surface. The final perovskite–silicon cell was 1 cm^2 in size. The nanoimprint techniques they used are relatively easy to scale up to a large area, Tockhorn says. "Many researchers from academia regard nanoimprint lithography as a very promising tool for solar cells due to its sheer simplicity and versality in terms of structure type."

Now that they have a proof-of-concept demonstration for making solution-based perovskite layers on textured silicon wafers, Tockhorn says they are working on improving the devices to boost efficiency even further. "We need to aim for a fully textured perovskite top cell that is textured at the front and at the interface between perovskite and silicon." ■

JOURNAL WATCH

App Senses COVID, Parkinson's in a Speaker's Voice

Two recent studies show that AI algorithms can successfully analyze voices to identify patients in the early stages of Parkinson's disease or a severe COVID-19 infection of the lungs. The researchers incorporated these algorithms into a smartphone app.

"This [approach] is not only to detect the disease but to evaluate the effects of medicine and to optimize the dosage," explains Dinesh Kumar, a professor at the Royal Melbourne Institute of Technology, in Australia, who was involved in both studies.

The first study, published on 12 September in *IEEE Access*, compared 36 people with Parkinson's disease with 36 healthy volunteers. To account for the natural differences in people's voices, the researchers asked subjects to utter phonemes that require specific sounds from the throat (/a/), mouth (/o/), and nose (/m/). The algorithm identified people with Parkinson's disease with 100 percent accuracy.

A similar study compared 40 hospitalized COVID-19 patients and 48 healthy subjects over the course of 22 days. The algorithm differentiated the two groups with 94 percent accuracy. These results were published on 20 September in the *IEEE Journal of Translational Engineering in Health and Medicine*.

—Michelle Hampson

ARTIFICIAL INTELLIGENCE

DeepMind Plays Math and Wins >

A game-playing algorithm accelerates matrix multiplication

BY CHARLES Q. CHOI

An artificial-intelligence system from Google's sibling company, DeepMind, has stumbled on a new way to solve a math problem at the heart of modern computing, a new study finds. The system outperformed an algorithm that hadn't been improved on for more than 50 years, researchers say.

The method involved a modification of DeepMind's AlphaZero, a game engine that had defeated grandmasters of chess and of the game of Go. It works by multiplying grids of numbers known as matrices, an operation that's key to processing images, recognizing speech commands, training neural networks, running simulations to predict the weather, and compressing data for sharing on the Internet.

"Finding new matrix-multiplication algorithms could help speed up many of these applications," says study lead author Alhussein Fawzi, a research scientist at DeepMind, a subsidiary of Google's parent company, Alphabet, and based in London.

The standard technique takes eight steps to multiply a pair of matrices that each have two rows and two columns. However, in 1969, the German mathematician Volker Strassen discovered a method that takes only seven steps. That's far more efficient, but for decades nobody could apply Strassen's breakthrough to the multiplication of larger matrices—even a pair of matrices as small as three by three, Fawzi says. "I felt from the very beginning that machine learning could help a lot in this field, by finding the best patterns—that is, which entries to combine in the matrices and how to combine them—to get the right result."

In the new study, Fawzi and his colleagues explored how AI might help automatically discover new matrix-multiplication algorithms. They built on Strassen's research, which focused on ways to break down 3D arrays of numbers called matrix-multiplication tensors into their elementary components.

The scientists developed an AI system dubbed AlphaTensor based on AlphaZero, which they had earlier developed to master chess, Go, and other games. They converted the problem of breaking down tensors into a single-player game and trained AlphaTensor to find efficient ways to win the game.

Fawzi's team noted that this game proved extraordinarily challenging. The number of possible algorithms that AlphaTensor must consider is far greater than the number of atoms in the universe, even for small cases of matrix multiplication. In one scenario, there

The number of possible algorithms that AlphaTensor must consider is far greater than the number of atoms in the universe, even for small cases of matrix multiplication.

DEEPMIND

Here, we show the standard algorithm compared with Strassen's algorithm, which uses one less scalar multiplication (seven instead of eight) for multiplying two-by-two matrices. Multiplications matter much more than additions for overall efficiency.

$$\begin{bmatrix} a_{1,1} & a_{1,2} \\ a_{2,1} & a_{2,2} \end{bmatrix} \times \begin{bmatrix} b_{1,1} & b_{1,2} \\ b_{2,1} & b_{2,2} \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} \\ c_{2,1} & c_{2,2} \end{bmatrix}$$

Standard algorithm	Strassen's algorithm
$h_1 = a_{1,1}\ b_{1,1}$	$h_1 = (a_{1,1} + a_{2,2})\ (b_{1,1} + b_{2,2})$
$h_2 = a_{1,1}\ b_{1,2}$	$h_2 = (a_{2,1} + a_{2,2})\ b_{1,1}$
$h_3 = a_{1,2}\ b_{2,1}$	$h_3 = a_{1,1}\ (b_{1,2} + b_{2,2})$
$h_4 = a_{1,2}\ b_{2,2}$	$h_4 = a_{2,2}\ (-b_{1,1} + b_{2,1})$
$h_5 = a_{2,1}\ b_{1,1}$	$h_5 = (a_{1,1} + a_{1,2})\ b_{2,2}$
$h_6 = a_{2,1}\ b_{1,2}$	$h_6 = (-a_{1,1} + a_{2,1})\ (b_{1,1} + b_{1,2})$
$h_7 = a_{2,2}\ b_{2,1}$	$h_7 = (a_{1,2} + a_{2,2})\ (b_{2,1} + b_{2,2})$
$h_8 = a_{2,2}\ b_{2,2}$	
$c_{1,1} = h_1 + h_3$	$c_{1,1} = h_1 + h_4 - h_5 + h_7$
$c_{1,2} = h_2 + h_4$	$c_{1,2} = h_3 + h_5$
$c_{2,1} = h_5 + h_4$	$c_{2,1} = h_2 + h_4$
$c_{2,2} = h_6 + h_8$	$c_{2,2} = h_1 - h_2 + h_3 + h_6$

were more than 10^{33} possible moves at each step of the game.

"The search space was gigantic," Fawzi says.

When the AI system began its operations, it had no knowledge about existing algorithms for matrix multiplication. By playing the game repeatedly and learning from the outcomes, it gradually improved. "AlphaTensor is the first AI system for discovering novel, efficient, and provably correct algorithms for fundamental tasks such as matrix multiplication," Fawzi says.

The system eventually discovered up to thousands of matrix-multiplication algorithms for each size of matrix it examined, revealing that the realm of matrix-multiplication algorithms was richer than previously thought. These included algorithms faster than any previously known. For example, AlphaTensor discovered an algorithm for multiplying 4-by-4 matrices in just 47 steps, improving on Strassen's 50-year-old algorithm, which uses 49.

"The first time we saw that we were able to improve over existing known algorithms was very exciting," Fawzi recalls.

These new algorithms possess a variety of different mathematical properties with a range of potential applications. The scientists modified AlphaTensor to find algorithms that are fast on a given hardware device, such as the Nvidia V100 GPU or Google TPU v2. They discovered algorithms that multiply large matrices 10 to 20 percent as fast as the commonly used algorithms on the same hardware.

"AlphaTensor provides an important proof of concept that with machine learning, we can go beyond existing state-of-the-art algorithms, and therefore that machine learning will play a fundamental role in the field of algorithmic discovery going forward," Fawzi says. "I believe that in the next few years, many new algorithms for fundamental computational tasks that we use every day will be discovered with the help of machine learning."

AlphaTensor started with no knowledge about the problem it tackled. This suggests that an interesting future direction might be to combine it with approaches that embed mathematical knowledge about the problem, "which will potentially allow the system to scale further," Fawzi says.

In addition, "we are also looking to apply AlphaTensor to other fundamental operations used in computer science," Fawzi says. "Many problems in computer science and math have similarities to the way we framed the problem in our research, so we believe that our paper will spur new results in mathematics and computer science with the help of machine learning."

The scientists detailed their findings on 5 October in the journal *Nature*. ■

Amazon Plans to Take Home Delivery to New Heights

By Willie D. Jones

In a world where some of us still remember being excited about 1-hour photo processing, Amazon is looking to make 1-hour delivery to our doorsteps a staple of e-commerce. The giant online retailer is always in the market for new technology aimed at making the company seem indispensable to the millions of people to whom it delivers goods each week. Pictured here are attendees at a 10 November 2022 Amazon showcase event called Delivering the Future. They're viewing a virtual-reality presentation about enhancements to Amazon's Prime Air drone delivery service. Expanding its smart-drone fleet will allow Amazon to scale up its same-day delivery service, making this option available for more products in more cities.

PHOTOGRAPH BY M. SCOTT BRAUER/ BLOOMBERG/GETTY IMAGES


prime air
prime air
prime air
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Careers

Arjun Pillai founded two software-as-a-service companies, both of which have been acquired.

Arjun Pillai › The entrepreneur shares lessons learned on his road to success

BY JOANNA GOODRICH

When Arjun Pillai was a youngster, the words *entrepreneur* and *startup* weren't part of his vocabulary. It wasn't until he went to college and joined a student chapter of the IEEE in 2006 that Pillai learned those terms.

After learning more about what running a tech company entails from other IEEE members, Pillai decided he also wanted to become an entrepreneur, to create "something bigger than me."

He went on to help launch two companies that develop software-as-a-service platforms—both of which he and his cofounders subsequently sold.

Pillai's most recent venture, Insent, was a business-to-business chat platform with offices in Denver; it was acquired in 2021 by software and data company ZoomInfo Technologies, of Vancouver, Wash. He is now senior vice president of ZoomInfo's product management and data.

Pillai started his career in 2010 at the IT company Infosys, in Bangalore, as a systems engineer, after he graduated from the Cochin University of Science and Technology in Kochi, Kerala, with a bachelor's degree in electronics and communication engineering.

But he never let go of the desire to become an entrepreneur, so he left Infosys in 2012 to found Profoundis with three former classmates. The company, also based in Kochi, aimed to help businesses and other organizations connect with customers. He served as chief executive officer.

"I was 23 years old. I was young and stupid and had no idea what I was getting into," Pillai says, laughing. During the company's first two years, it developed four products—a management system for online testimonials, a financial analytics platform for small and midsize businesses, an assignment system for college students, and a social-media analytics tool. All of them flopped, Pillai says.

"But we had to just keep going," he says. "The failure didn't really register as such. It was just another day at work."

In 2015, Profoundis launched its fifth product, Vibe. The sales software, which helps businesses identify prospective customers, proved to be a winner. Vibe collects data about companies from the Internet, organizes it into a searchable list, and makes it available to marketers and salespeople. More than 200 companies in dozens of countries have used it. The success of the product enabled Profoundis to grow from seven employees to 72. FullContact, a software company in Denver, acquired Profoundis in 2016.

"It was the first product acquisition in the history of my state of Kerala," Pillai says.

After Profoundis was sold, Pillai joined FullContact as the head of data strategy, working in Denver. But he says he didn't really enjoy working for another company.

"Once you're an entrepreneur, you kind of have that bug all the time," he says. He also struggled with the fact that it wasn't his company anymore, he says.

"I didn't do a good enough job transitioning from CEO to employee," he says. "I always tell other entrepreneurs about my experience so they don't make the same mistake. This was the most important thing I learned after selling my first company."

Pillai left FullContact after two years and worked as a consultant until 2018, when he founded Insent with Prasanna Venkatesan. The two cofounders had met through their volunteer activities

ARJUN PILLAI

"If the reason why you started a company is strong, it will get you through the hurdles you will face."

with IEEE a decade earlier.

The startup's B2B platform used a combination of human and chatbot conversations to personalize a customer's purchasing experience with a retailer. After Insent was acquired, the platform was renamed ZoomInfo Chat.

ZoomInfo hired all of the startup's employees. In his new position, Pillai led the release of ZoomInfo Chat. He is currently managing the company's data portfolio. "ZoomInfo has the best business data assets in the world," he says. "It's the core of the company, so I have a big responsibility."

Pillai, who had no mentor to teach him how to run a company, is now a strong advocate for supporting budding entrepreneurs. For the past five years, he has been an ambassador for Start-Up Chile, a government initiative that seeks to attract high-potential entrepreneurs to the country. "I want to give back," he says.

The biggest challenge for any startup, he says, is bringing together the right team, especially if you plan to launch the company with another person. "Being cofounders is like being married," he says. "If you choose the wrong person, running a successful startup together will be difficult."

You need to pick people who share your passion and have a similar mindset, a positive attitude, and strong ethics, he says.

Other challenges include developing a product or service that makes sense for its intended market and securing enough funding so that you can release the product in a timely way while it still can make an impact.

Pillai tells budding entrepreneurs to make sure they're forming a company for the right reasons. Found a startup only if "you feel passionate about a problem that keeps you awake at night and that you believe you're the only person who can solve," he says. "If the reason why you started a company is strong, it will get you through the hurdles you will face."

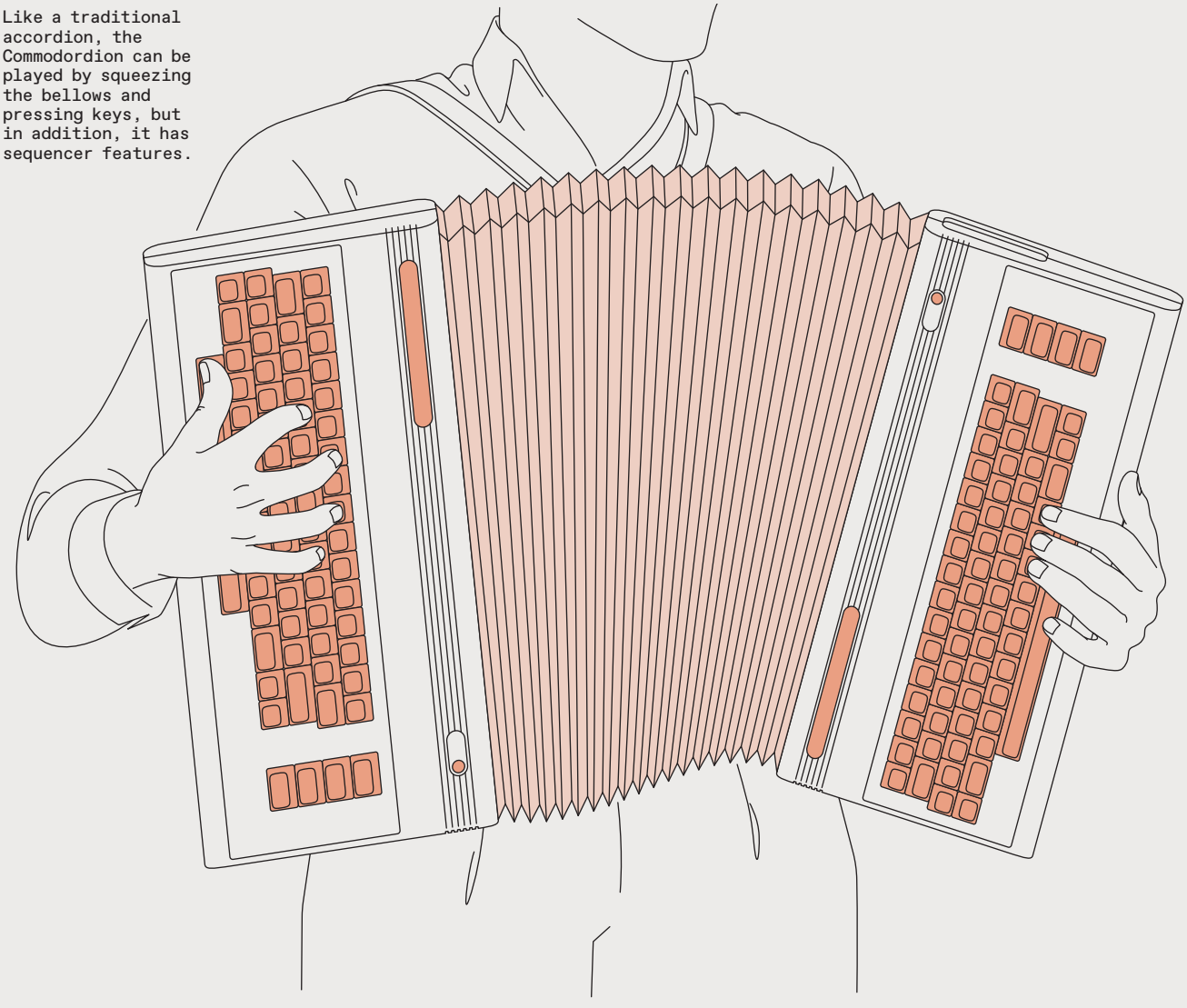
Pillai also advises startup founders to take occasional breaks from work.

"In the four and a half years I was CEO of my first company, work was my life," he says. He was so driven that he showed up once to an investor's meeting while he was sick, instead of rescheduling it. He thinks that's the reason the investor didn't back the project.

Pillai says he wishes he'd had a mentor to tell him he needed to take it easy, and things would work out in the end.

"Learning all these lessons on my own was a humbling experience." ■

Hands On



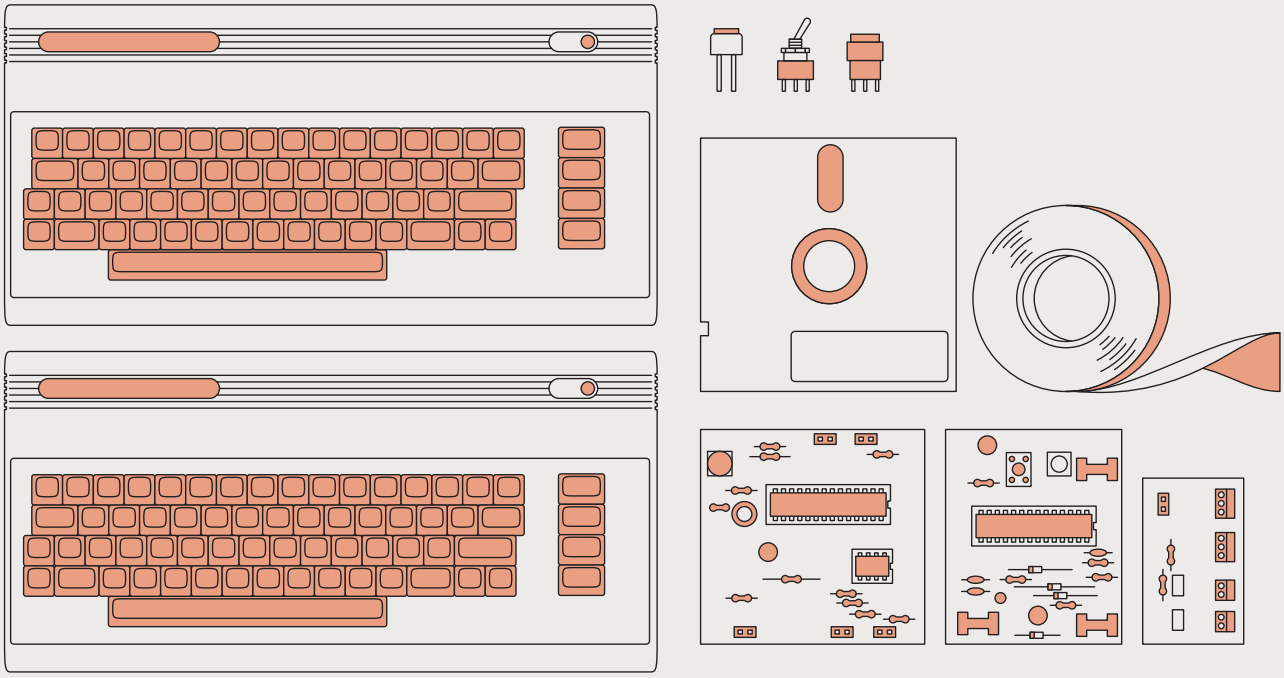
Like a traditional accordion, the Commodordion can be played by squeezing the bellows and pressing keys, but in addition, it has sequencer features.

The Commodordion › Two C64s Plus Some Floppy Disks Equals One Instrument

BY LINUS AKESSON

Accordions come in many shapes. Some have a little piano keyboard while others have a grid of black and white buttons set roughly in the shape of a parallelogram. I've been fascinated by this "chromatic-button" layout for a long time. I realized that the buttons are staggered just like the keys on a typewriter, and this insight somehow turned into a blurry vision of an accordion built from a pair of 1980s home computers—

Illustrations by James Provost



In addition to two vintage Commodore 64s [left], the Commodordion has a microphone for detecting air flow through the bellows, and buttons for turning on the power and controlling a tape-deck emulator [top right]. The bellows are made from tape and 5.25-inch floppy disks [middle right]. One supporting board incorporates a microcontroller to measure the airflow and mix the audio signals, a second stores the accordion software and emulates a cassette player, and a third acts as a power hub.

these machines typically sported a built-in keyboard in a case big enough to form the two ends of an accordion. The idea was intriguing—but would it really work?

I'm an experienced Commodore 64 programmer, so it was an obvious choice for me to use that machine for the accordion ends. As a retrocomputing enthusiast, I wanted to use vintage C64s with minimal modifications rather than, say, gutting the computer cases and putting modern equipment inside.

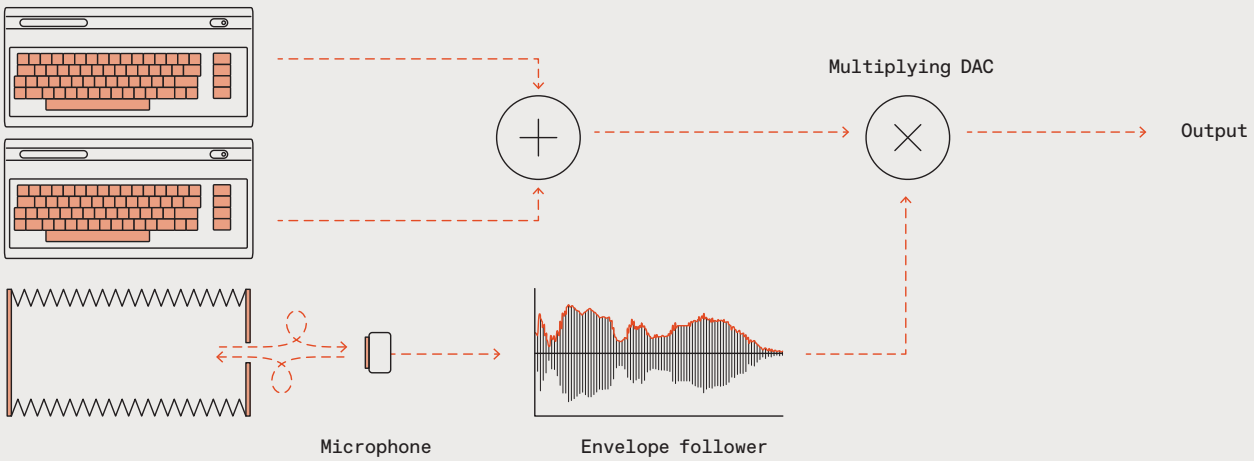
As for what would go between the ends, accordion bellows are a set of semirigid sheets, typically rectangular with an opening in the middle. The sheets are attached to each other alternating between the inner and outer edges. Another flash of insight: The bellows could be made from a stack of 5.25-inch floppy disks.

Now I had several compelling ideas that seemed to work together. I secured a large quantity of bad floppies from a fellow C64 enthusiast. And then, armed with everything I needed and eager to start, I was promptly distracted by other projects.

Some of these projects involved ways of playing music live on C64 computers. The idea to model a musical keyboard layout after the chromatic-button accordion became a standalone C64 program released to the public called Qwertuoso.

That could well have been the end of it, but I had all these disks on my hands, so I decided to go ahead and try to craft a bellows after all. The body of a floppy disk is made from a folded sheet of plastic, and together these form the bellow's segments. But I had underestimated the problem of air leakage. While the floppy-disk material is airtight, the seams aren't. In the end I had to patch the whole thing up with multiple layers of tape to get the air to stay inside.

A real accordion uses the bellows to push air over reeds to make them vibrate. How fast the bellows is pumped determines the accordion's loudness. So I needed a way to sense how fast air was



The Commodordion is played by using the keys on the Commodore 64s and squeezing the bellows between. Air moving through the bellows creates a loud or soft noise depending on how hard the bellows are squeezed. A microcontroller running an envelope-following program controls a multiplying digital-to-audio converter that sets the final volume of the combined sound from the C64s.

being squeezed out of my floppy-disk bellows as I played.

This was trickier than I had anticipated. I went through several failed designs including one inspired by the "hot wire" sensors used in fuel-injection systems. Then one day, I was watching a video and I realized that a person in the video was shouting in order to overcome noise caused by wind hitting his microphone. That was the breakthrough I needed! The solution turned out to be a small microphone, mounted at an angle just outside a small hole in the bellows.

Air flowing into or out of the hole passes over the microphone, and the resulting turbulence turns into audio noise. The intensity of the noise is measured, in my case by an ATmega88 microcontroller, and is used to determine the output volume of the instrument.

The bellows is attached to a simple frame built from wood and acrylic, which also holds the C64s as well as three boards with supporting electronics. One of these is a power hub that takes in 5 and 12 volts of DC electricity from two household-power adapters and distributes it to the various components. For ergonomic reasons, rather than using the normal socket on the C64s right-hand sides, I fed power into the C64s by wires passed through the case and directly soldered to the motherboards.

A second board emulates Commodore's datasette tape recorder. This stores the Qwertuoso program. Once the C64s are turned on, a keyboard shortcut built into the original OS directs the computer to load from tape. The final board contains the microcontroller monitoring the bellows' microphone and mixers that combine the analog sound generated by each C64's 6581 SID audio chip and adjusts the volume as per the bellows air sensor. The audio signal is then passed to an external amplified loudspeaker to produce sound.

In order to reach the keys on the left-hand side when the bellows is extended, my hand needs to bend quite far around the edge of what I dubbed the Commodordion. This puts a lot of strain on the hand, wrist, and arm. Partly for this reason, I developed a sequencer for the left-hand-side machine, whereby I can program a simple beat or pattern and have it repeat automatically. With this, I only have to press keys on the left-hand side occasionally, to switch chords.

As a musician, I have to take ergonomics seriously. When you learn to play a piece of music, you practice the same motions over and over for hours. If those motions cause strain you can easily ruin your body. So, unfortunately, I have to restrict myself to playing the Commodordion only occasionally, and only play very simple parts with the left hand.

On the other hand, the right-hand side feels absolutely fine, and that's very encouraging: I'll use that as a starting point as I continue to explore the design space of instruments made from old computers. In that light, the Commodordion wasn't the final goal after all, but an important piece of scaffolding for my next creative endeavor. ■

Armed with everything I needed and eager to start, I was promptly distracted by other projects.

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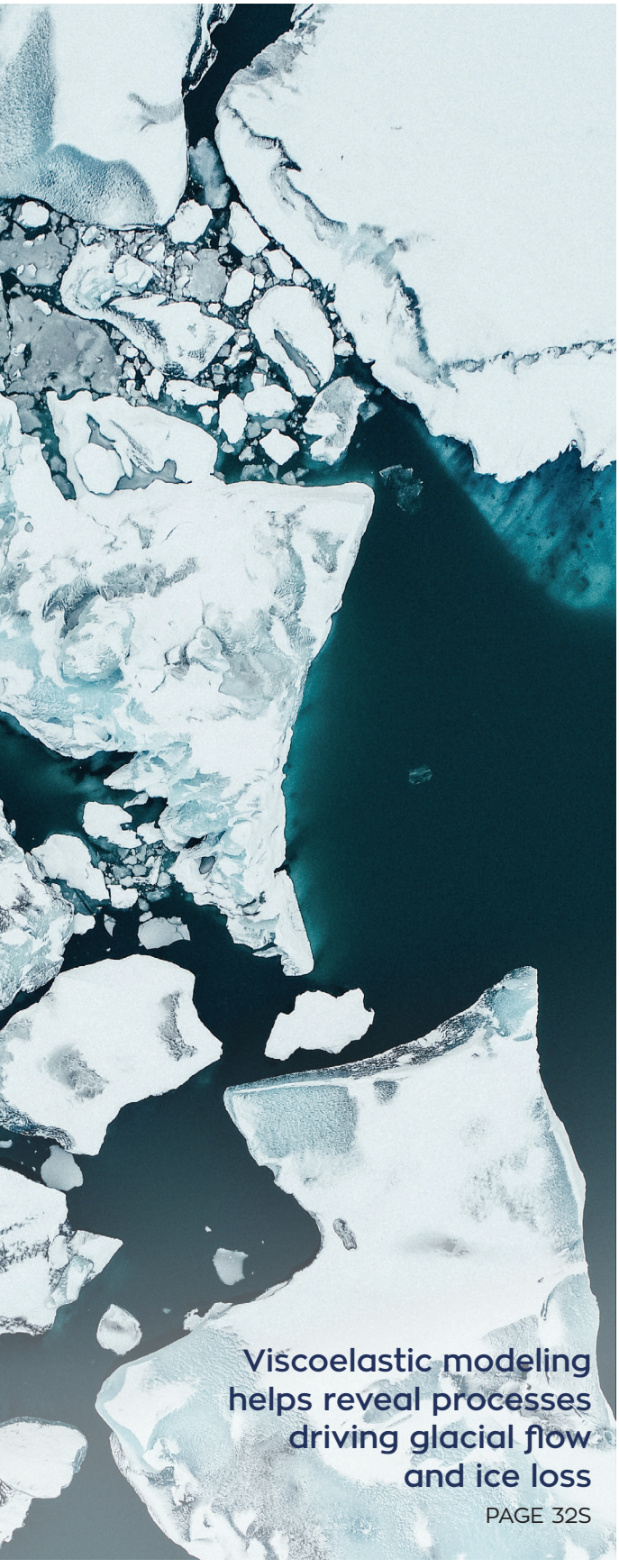

Viscoelastic modeling helps reveal processes driving glacial flow and ice loss

PAGE 32S

As Global Challenges Intensify, Innovators Step Up

What defines a decade? The 2020s have hardly begun, yet we have already witnessed dramatic changes. The long-predicted effects of climate change are reshaping lives worldwide, even as we also confront unexpected crises like the global pandemic.

But is an era defined only by its difficulties? History suggests that how we *respond* to difficulties may be just as important. In this year's COMSOL News, we present nine stories of people who are stepping up to meet the challenges of our time — with help from multiphysics simulation.

Some of them are directly researching the effects of climate change, such as Angelika Humbert of the Alfred Wegener Institute, whose team is modeling the viscoelastic forces that are reshaping Greenland's glaciers. Others, including teams at companies like Exicom and Bosch, are developing electric vehicle technology to help reduce dependence on fossil fuels. There are also startups like Polar Night Energy of Finland, whose ingenious system stores solar-generated heat inside a "battery" made from sand. Other innovators are tackling perpetual challenges, such as health care and communications, with promising new technologies.

All of these R&D stars are striving to craft a brighter future — and they're doing it with help from the COMSOL Multiphysics® software. Even those who are new to simulation are putting its power to work; on page 8s, learn how England's Manufacturing Technology Centre has empowered factory workers with an app that can serve as a prototype "digital twin" of their facility.

Perhaps if we can take inspiration from innovators like these, we will remember this era not for its setbacks, but for the steps being taken to help build a better world.

Alan Petrillo
COMSOL, Inc.

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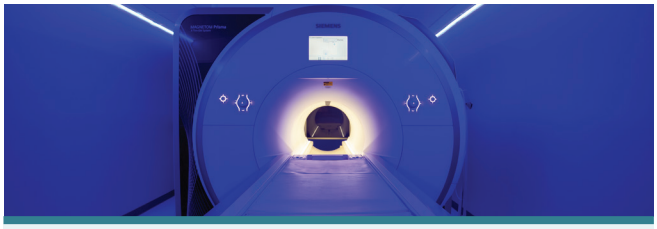
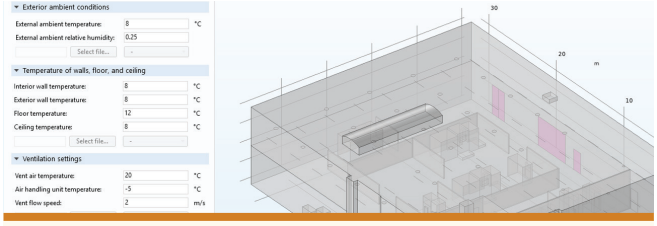


DESIGN OPTIMIZATION



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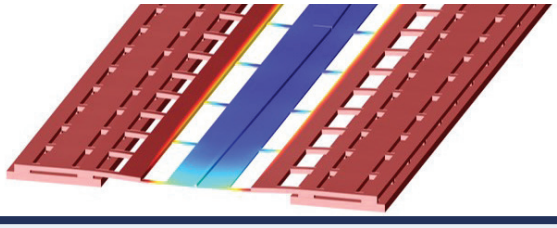
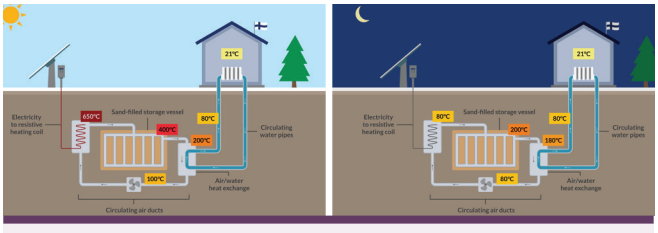


SIMULATION-BASED PRODUCT DEVELOPMENT



RESEARCH SPOTLIGHT

GUEST EDITORIAL

Bosch, Germany

BOSCH POWERS THE AUTOMOTIVE SECTOR TOWARD AN ELECTRIFIED FUTURE

The global transition toward electric cars is getting a boost from industry suppliers like Robert Bosch, which provides electrical components and systems to car manufacturers. The Bosch team optimizes three-phase inverters and DC link capacitors with a simulation-powered design process, which enables them to identify potentially destructive "hot spots" early in the development cycle.

by **ALAN PETRILLO**

Just as tourists in Paris are drawn to the Louvre, visitors to Stuttgart, Germany, also flock to museums displaying the great works of the city. Stuttgart may not boast of Degas or Monet, but its prominent names are perhaps even more famous than Paris' painters: Mercedes–Benz and Porsche. Each of these iconic automakers maintains a museum in the southwestern German city they call home. Their gleaming galleries feature many historic and influential cars, almost all of them powered by petroleum-fueled internal combustion (IC) engines. Looking ahead, Stuttgart will likely continue to be the heart of the German auto industry, but how long will the IC engine remain the heart of the automobile?

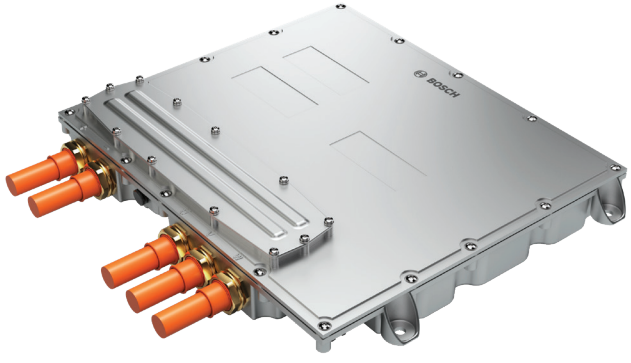


FIGURE 1 A Bosch three-phase inverter for automotive drivetrains.

Even the most successful manufacturers must adapt to changing conditions. The German automotive sector, along with its global counterparts, is doing so by developing *elektrische autos*. Electric cars are an important focus of Robert Bosch — another leading automotive company founded in Stuttgart. Today, Bosch supplies electric powertrains, systems, and components to automakers worldwide.

As the automotive industry races toward an electrified future, Bosch is accelerating its R&D into the essential building blocks of electric drivetrains. One of these components is the inverter, which changes direct current (DC) from the car's batteries into alternating current (AC) to power its drive motor (Figure 1). The inverter's ability to provide a smooth flow of current depends on its integral DC link capacitor (Figure 2). "The capacitor is one of the most expensive components of the inverter. Its performance has a direct impact on the performance and reliability of the inverter, which is fundamental to the operation of the drivetrain," explains Martin Kessler, Bosch senior expert for automotive electronics.

For the global automotive sector to meet its ambitious electrification goals, inverters and their capacitors must undergo continuous improvement and optimization. Martin Kessler and his team rely on multiphysics simulation to test and refine Bosch's DC link capacitors. Their simulation-enabled predictive analysis complements and optimizes the live

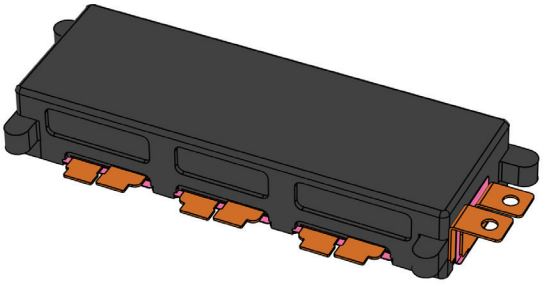


FIGURE 2 A typical DC link capacitor, with a battery interface on the right and transistor connectors on the front.

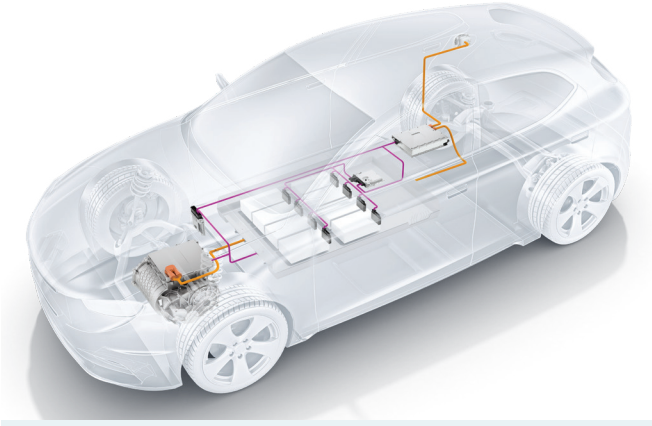


FIGURE 3 The path of current through a generic electric drivetrain. The path flows from a charger-converter, at right, to the battery shown at the center of the car. The battery provides DC to a three-phase inverter mounted above the drive motor assembly. The inverter converts DC into three-phase AC to power the car's drive motor.

prototyping of new designs. "It is simply not possible to predict potential problems with testing alone; we need both simulation and prototyping working hand in hand," says Kessler.

» THE EMERGING ERA OF THE ELECTRIC AUTOMOBILE

"Drivers, start your engines!" As if heeding the call to begin a worldwide race, people everywhere begin their days by firing up a rumbling IC engine. But this familiar sound can seem ominous, especially as the environmental impact of vehicle emissions grows more apparent. To lessen these emissions and their contribution to global climate change, the automobile industry is ramping up the production of electric-powered cars and trucks. Many of the electric vehicles available today have familiar brand names, but under the hood, these cars often rely on the technology and expertise of outside suppliers.

It is worth noting just how significant a shift this is for a major global industry. Leading automakers are some of the world's largest employers, and a vast share of their workers, R&D, and production capacity is dedicated to producing IC engines. The centrality of internal combustion to these companies can be found in their names, from General Motors to Bayerische Motoren Werke (better known as BMW). Why would companies known for their engines turn to outsiders to make their cars go? Perhaps it is because, in a sense, electrification is forcing the industry to learn how to produce an entirely different type of machine.

» ANATOMY OF AN ELECTRIC DRIVETRAIN

To make a fully electric car, it is not enough to replace the engine with an electric motor and the gas tank with a battery. Such familiar devices are only parts of a larger system, which helps deliver smooth, reliable performance by adjusting to the constantly varying conditions under which every vehicle must operate (Figure 3).

» INDISPENSABLE INVERTER, CRUCIAL CAPACITOR

The role of the inverter in an automotive drivetrain is simple in concept, but complex in practice (Figure 4). The inverter must satisfy the AC demands of the motor with the DC provided by the battery, but it must also adjust to ongoing fluctuations in load, charge, temperature, and other factors that can affect the behavior of each part of the system. All of this must occur within tight cost and spatial constraints, and the component must sustain this performance for years to come.

To understand the inverter's function, consider what a three-phase AC motor needs in order to operate. If connected to DC, the motor simply will not rotate. Instead, it must be provided with alternating current with three distinct but complementary waveforms, enabling the motor's three-part field coil to magnetically attract the segments of its rotor in a sequential pattern. "To control the activity of the motor, we must control the amplitude and frequency of the inverter's current output," explains Kessler. "The speed of the motor is proportional to frequency, while amplitude helps determine its torque."

"The desired current waveform through the transistors has a relatively steep gradient. The only way to achieve switch-mode current with this high gradient is to have very low inductance in the source path," Kessler says. Inductance is the particular force opposing changes in current flow. Every slight change in current will be limited by an induced counteracting voltage, which will disrupt the desired waveform — and the smooth rotation of the motor.

To reduce the inductance in the source path of the transistors, a capacitor is placed in parallel across the input lead from the battery, which is called the DC link. The DC link capacitor (Figure 5) is placed in direct proximity to the transistors and provides the desired current waveforms through the transistors. The low impedance of the capacitor minimizes any remaining ripple voltage on the battery side.

A typical capacitor consists of two electrodes separated by an insulating gap, which may simply be airspace or some kind of material. In this application, Bosch uses capacitors made with metallized polypropylene film. A thin coating of metal (forming the electrodes) is sprayed on each side of the film, which provides the necessary dielectric gap. The metallized film is then wound tightly into a canister shape. As with the inverter itself, the capacitor's conceptual simplicity conceals a multifaceted engineering design problem.

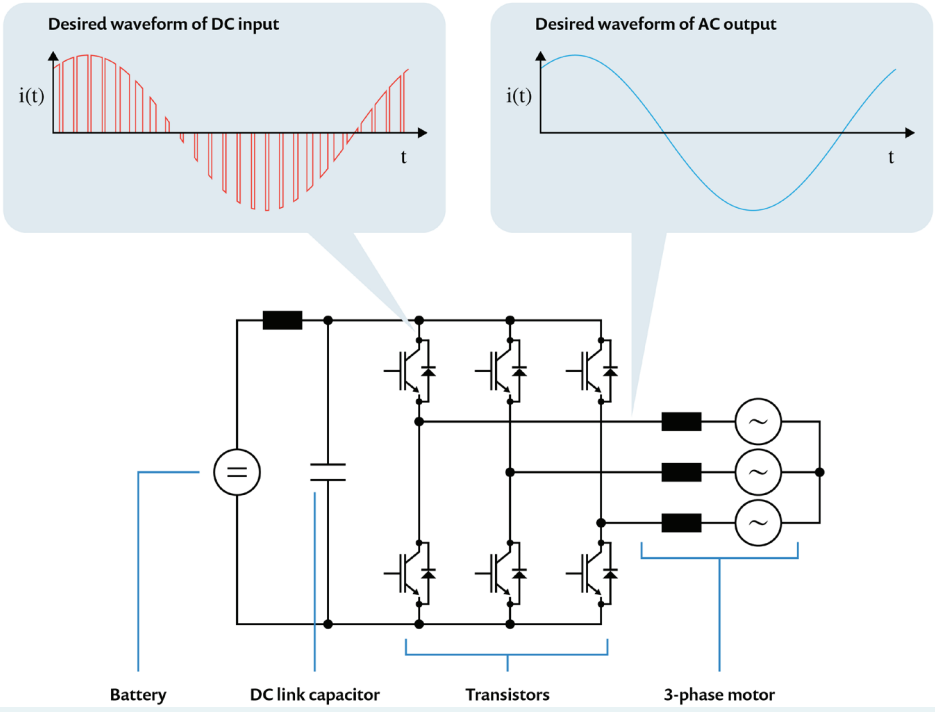


FIGURE 4 Inside a three-phase inverter, DC from the battery is converted to three-phase AC by three sets of transistors. By switching on and off in sequence, the transistors produce AC in three distinct phases, causing the car's drive motor to rotate. The DC link capacitor helps manage the input current.

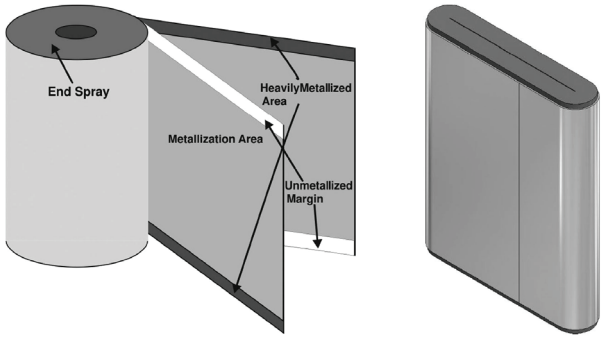


FIGURE 5 DC link capacitors are made from metallized polypropylene film, which is wound into an elongated canister shape.

» CHALLENGES OF DC LINK CAPACITOR DESIGN FOR VEHICLE INVERTERS

Capacitors are widely available components that are installed in countless electronic devices. For the past seven years, Martin Kessler has been responsible for DC link capacitor design at Bosch. He has been with the company since 1989 and has worked on electric car technology since 2010. That such an experienced engineer is dedicated to this one component shows its importance — and its complexity.

"Why can we not just pick up a capacitor from the marketplace?" asks Kessler, rhetorically. "There are multiple interdependent factors at work. First, we have high demands for performance and reliability. Second, there are very tight spatial requirements. Third, we face difficult thermal constraints, as the polypropylene film in a capacitor can only withstand temperatures up to around 105°C. This issue is compounded by the interaction of electromagnetic and thermal activity throughout the inverter. And finally, the capacitor is relatively expensive," Kessler explains.

» SIMULATION (NOT LUCK) HELPS SOLVE THE BLACK BOX PROBLEM

To meet the design challenges of a DC link capacitor, Kessler developed a process that combines experimental testing with multiphysics simulation. As an example of why simulation-based analysis is a necessary part of his work, he cites the difficulty of finding and measuring potential hot spots, where high heat and coupled effects can cause failures. "We try to locate hot spots by placing a lot of thermocouples inside prototypes and measuring temperatures at various load points," Kessler says. "But my mantra is that you will never find a hot spot like this without a lot of luck! You will need to be lucky to place the thermocouple in the right position," he laughs.

"A simple 2D model of a capacitor is also insufficient," Kessler continues. "The inverter is a distributed system with internal resonances and a complex loss distribution. Our coupled EM and thermal analysis must account for skin effects and proximity effects. We cannot calculate an absolute value for peak temperatures without a 3D finite element approach, which also enables us to model the spatial distribution of coupled EM and thermal effects. This is an ideal task for the COMSOL Multiphysics® software," Kessler says (Figures 6–7).

Kessler's design process validates simulation models against measured results, where possible, and then uses the validated models to pinpoint potential problems (Figure 8). "By helping us locate hot spots in the model, the simulation helps us avoid issues that would have appeared late in the development process, or even after production had started," says Kessler. "Instead, we can get specific results and make adjustments early in the process."

"We perform EM modeling and validation of every new design. We compare the calculated equivalent series resistance (ESR) curve with the ESR curve as measured

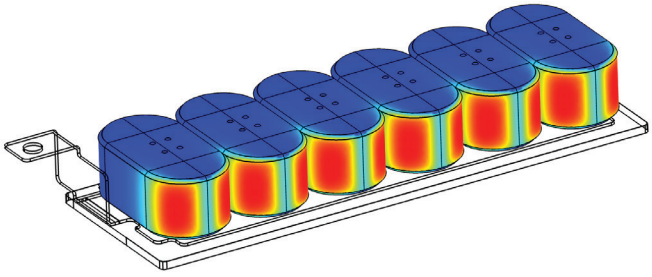


FIGURE 6 3D model image showing simulation of EM effects inside a DC link capacitor design.

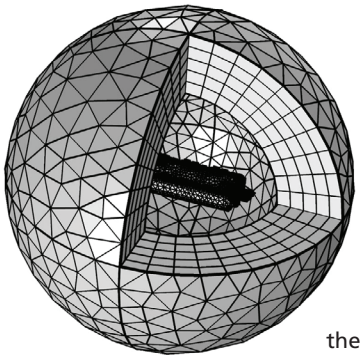


FIGURE 7 A model of the electromagnetic field generated by the capacitor, which aids the calculation of loss distribution in the unit.

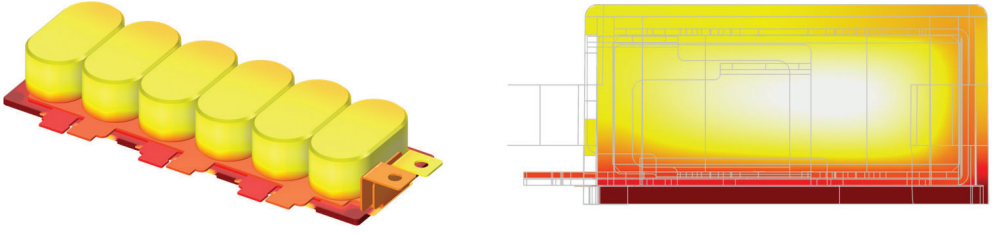


FIGURE 8 A 3D model showing simulation of thermal effects inside a DC link capacitor design, and a cutaway view showing the hotspot location in the capacitor.

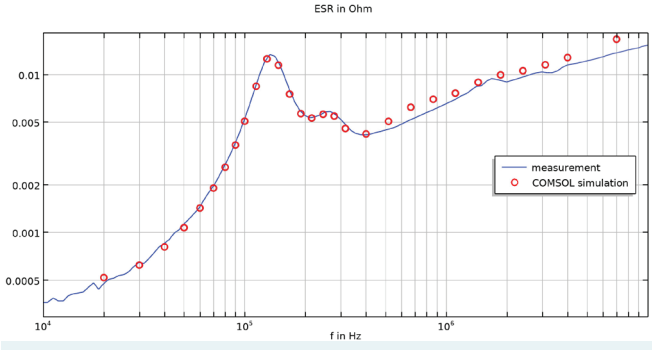


FIGURE 9 A plot of the ESR curve, as calculated in the simulation, compared with ESR values derived from measurement of a live prototype. Alignment of these curves helps validate the model for further analysis.

from a prototype (Figure 9). If these curves are aligned, we can set up boundary conditions for stationary and transient heat calculations," says Kessler. "We can compare the temperature curves from our thermocouples with the results of probes in the COMSOL Multiphysics model. If they match, we can then simulate all the critical points where we must keep temperatures within limits." The curve data is put into the COMSOL Multiphysics software via the LiveLink™ *for* MATLAB® interfacing product.

"Before we can do this, we have to think about which factors should be incorporated into the model," says Kessler. "Some of the variables we receive from the OEM, such as maximum DC link voltage, are not very relevant to our simulation," he continues. "But the current, switching frequency, e-machine values, and modulation schemes all help define a current spectrum. We need to calculate the current spectrum for all three phases of our output in order to establish power losses. Once we have this, we can do the harmonic analysis with COMSOL Multiphysics for the frequencies of the current spectrum. Then we sum up our losses for every harmonic," Kessler explains.

Other important values include the boundary conditions, which help Kessler and his team determine coupled effects. "We calculate parasitic inductance of the capacitor with the AC/DC Module," Kessler says. "We also find the complete AC loss distribution through the capacitor windings or internal busbar. Then we can couple the results and determine a temperature-dependent resistivity of the cover parts with the Heat Transfer Module," he says. "This enables us to establish the maximum element hot spot temperature resulting from the EM activity."

Findings from their analyses can then lead to design changes. Kessler explains that each new capacitor design typically undergoes three rounds of testing. "With simulation, the improvement curve gradient is much steeper from one phase to the next. Our knowledge grows quickly, and this is reflected in the final product." The latest generation of Bosch inverters promises 6% greater range and a 200% jump in power density compared to previous designs.

» ELECTRIFICATION SHIFTS INTO HIGH GEAR

As automakers convert more of their product lines to electric propulsion, Martin Kessler believes that the need for rapid, cost-conscious R&D will also increase. "Electric mobility is growing up now," he says. "We expect that the OEMs will come to us with more varied needs, for inverters in different power classes and that meet tighter spatial constraints," says Kessler. "I do think that the number of products that require new capacitor designs will keep expanding. With our simulation-driven development methods, we are confident that we can keep up with this growth."

In the years to come, perhaps visitors to Stuttgart's car museums will stop to admire the historic motors and inverters that powered the industry into a new electric age.

Manufacturing Technology Centre, United Kingdom

FINE-TUNING THE FACTORY: A SIMULATION APP HELPS OPTIMIZE AN ADDITIVE MANUFACTURING FACILITY

Additive manufacturing (AM) processes, such as metal powder bed fusion, can provide rapid and customizable production of high-quality components. Britain's Manufacturing Technology Centre, along with partners in the aerospace sector, has built an on-site powder bed fusion facility — and also developed a simulation model and app to help factory staff make informed decisions about its operation.

by **ALAN PETRILLO**

History teaches that the Industrial Revolution began in England in the mid-18th century. While that era of sooty foundries and mills is long past, manufacturing remains essential — and challenging. One promising way to meet modern industrial challenges is by using additive manufacturing (AM) processes, such as powder bed fusion and other emerging techniques. To fulfill its promise of rapid, precise, and customizable production, AM demands more than just a retooling of factory equipment; it also calls for new approaches to factory operation and management.

That is why Britain's Manufacturing Technology Centre (MTC) has enhanced its in-house metal powder bed fusion AM facility with a simulation model and app to help factory staff make informed decisions about its operation. The app, built using the Application Builder in the COMSOL Multiphysics® software, shows the potential for pairing a full-scale AM factory with a so-called "digital twin" of itself.

"The model helps predict how heat and humidity inside a powder bed fusion factory may affect product quality and worker safety," says Adam Holloway, a technology manager within the MTC's modeling team. "When combined with data feeds from our facility, the app helps us integrate predictive modeling into day-to-day decision-making." The MTC project demonstrates the benefits of placing simulation directly into the hands of today's industrial workforce and shows how simulation could help shape the future of manufacturing.

» ADDITIVE MANUFACTURING FOR AEROSPACE WITH DRAMA

To help modern British factories keep pace with the world, the MTC promotes high-value manufacturing throughout the United Kingdom. The MTC is based in the historic English industrial city of Coventry (Figure 1), but its focus is solely on the future. That is why the team has committed significant human and technical resources to its National Centre for Additive Manufacturing (NCAM).

"Adopting AM is not just about installing new equipment. Our clients are also seeking help with implementing the digital infrastructure that supports AM factory operations," says Holloway. "Along with enterprise software and data connectivity, we're exploring how to embed simulation within their systems as well."

The NCAM's Digital Reconfigurable Additive Manufacturing for Aerospace (DRAMA) project provides a valuable venue for this exploration. Developed in concert with numerous manufacturers, the DRAMA initiative includes the new powder bed fusion AM facility mentioned previously. With that mini factory as DRAMA's stage, Holloway and his fellow simulation specialists play important roles in making its production of AM aerospace components a success.

FIGURE 1 The headquarters of the Manufacturing Technology Centre in Coventry, England.

FIGURE 2 An example of a part produced through the metal powder bed fusion process.

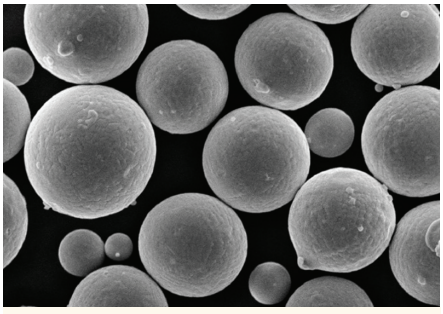


FIGURE 3 A microscopic close-up of powdered metal grains, as used for powder bed fusion.

» MAKING SOFT MATERIAL ADD UP TO SOLID OBJECTS

What makes a manufacturing process "additive", and why are so many industries exploring AM methods? In the broadest sense, an additive process is one where objects are created by adding material layer by layer, rather than removing it or molding it. A reductive or subtractive process for producing a part may, for example, begin with a solid block of metal that is then cut, drilled, and ground into shape. An additive method for making the same part, by contrast, begins with empty space! Loose or soft material is then added to that space (under carefully controlled conditions) until it forms the desired shape. That pliable material must then be solidified into a durable finished part.

Different materials demand different methods for generating and solidifying additive forms. For example, common 3D printers sold to consumers produce objects by unspooling warm, plastic filament, which bonds to itself and becomes harder as it cools. By contrast, the metal powder bed fusion process begins with, as its name suggests, a powdered metal which is then melted by applied heat and re-solidified when it cools. A part produced via the metal powder bed fusion process can be seen in Figure 2.

» HOW HEAT AND HUMIDITY AFFECT METAL POWDER BED FUSION

"The market opportunities for AM methods have been understood for a long time, but there have been many obstacles to large-scale adoption," Holloway says. "Some of these obstacles can be overcome during the design phase of products and AM facilities. Other issues, such as the impact of environmental conditions on AM production, must be addressed while the facility is operating."

For instance, maintaining careful control of heat and humidity is an essential task for the DRAMA team. "The metal powder used for the powder bed fusion process (Figure 3) is highly sensitive to external conditions," says Holloway. "This means it can begin to oxidize and pick up ambient moisture even while it sits in storage, and those processes will continue as it moves through the facility. Exposure to heat and moisture will change how it flows, how it melts, how it picks up an electric charge, and how it solidifies," he says. "All of these factors can affect the resulting quality of the parts you're producing."

Careless handling of powdered metal is not just a threat to product quality. It can threaten the health and safety of workers as well. "The metal powder used for AM processes is flammable and toxic, and as it dries out, it becomes even more flammable," Holloway says. "We need to continuously measure and manage humidity levels, as well as how loose powder propagates throughout the facility."

To maintain proper atmospheric conditions, a manufacturer could augment its factory's ventilation with a full climate control system, but that could be prohibitively expensive. The NCAM estimated that it would cost nearly half a million English pounds to add climate control to its relatively modest facility. But what if they could adequately manage heat and humidity without adding such a complicated system?

» RESPONSIVE PROCESS MANAGEMENT WITH MULTIPHYSICS MODELING

Perhaps using multiphysics simulation for careful process management could provide a cost-effective alternative. "As part of the DRAMA program, we created a model of our facility using the computational fluid dynamics (CFD) capabilities of the COMSOL® software. Our model (Figure 4) uses the finite element method to solve partial differential equations describing heat transfer and fluid flow across the air domain in our facility," says Holloway. "This enabled us to study how environmental conditions would be affected by multiple variables, from

"We're trying to present the findings of some very complex calculations in a simple-to-understand way. By creating an app from our model, we can empower staff to run predictive simulations on laptops during their daily shifts."

— ADAM HOLLOWAY, MTC TECHNOLOGY MANAGER

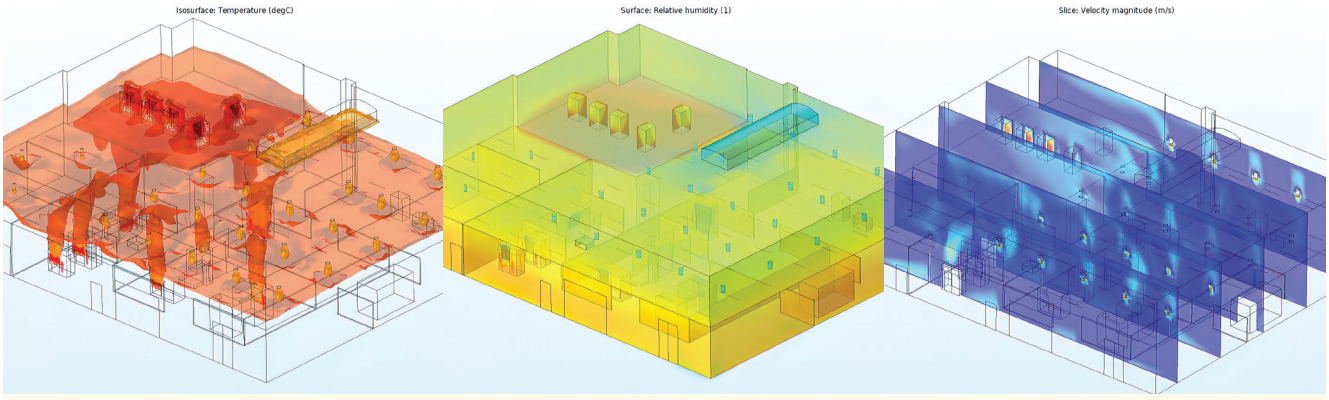


FIGURE 4 Three simulation images of the DRAMA facility with seven machines operating. At left is an isosurface plot showing temperature variations. The center image shows the distribution of humidity variations, and the image at right is a slice plot showing airflow velocity throughout the space.

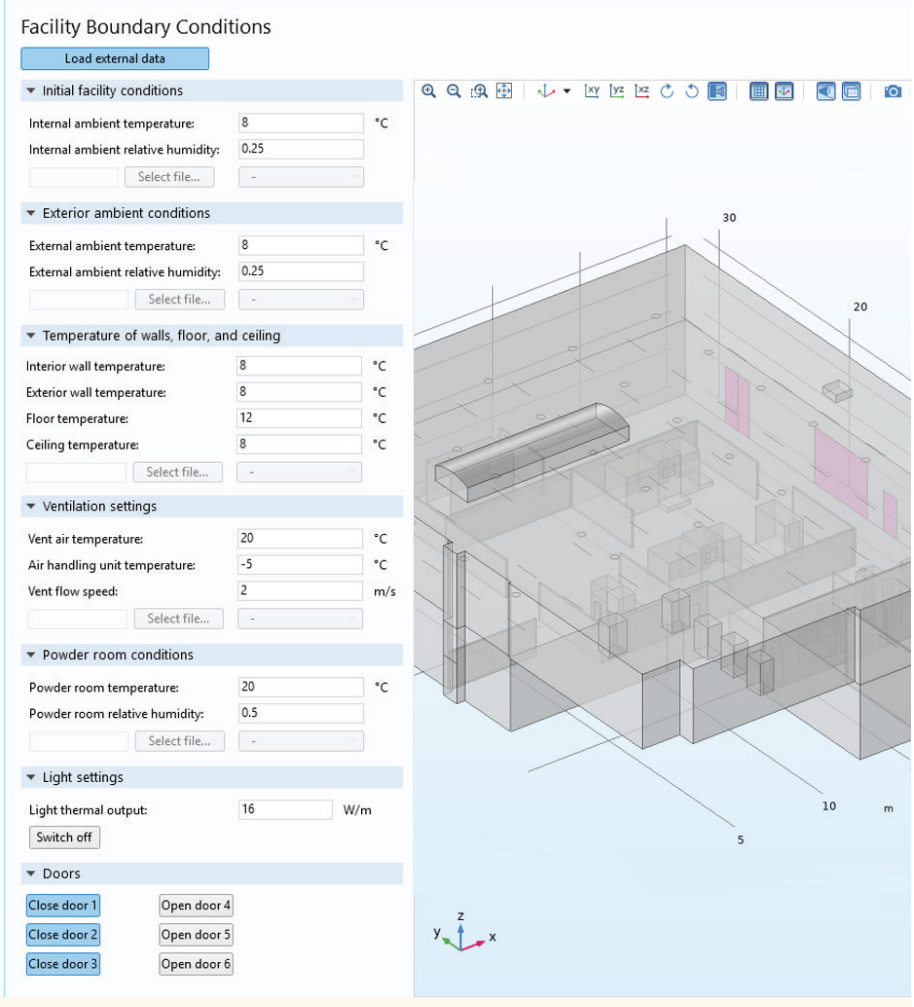


FIGURE 5 A simulation app of the DRAMA powder bed fusion facility, showing the machines it contains and the locations of the air vents. Users can specify the initial temperature and humidity throughout the space, along with settings for the air handling system, lights, and metal powder storage room. In this case, some doors (highlighted in pink) have been left open.

the weather outside, to the number of machines operating, to the way machines were positioned inside the shop. A model that accounts for those variables helps factory staff adjust ventilation and production schedules to optimize conditions," he explains.

» A SIMULATION APP THAT EMPOWERS FACTORY STAFF

The DRAMA team made their model more accessible by building a simulation app of it with the Application Builder in COMSOL Multiphysics (Figure 5). "We're trying to present the findings of some very complex calculations in a simple-to-understand way," Holloway explains. "By creating an app from our model, we can empower staff to run predictive simulations on laptops during their daily shifts."

The app user can define relevant boundary conditions for the beginning of a factory shift and then make ongoing adjustments. Over the course of a shift, heat and humidity levels will inevitably fluctuate. Perhaps factory staff should alter the production schedule to maintain part quality, or maybe they just need to open doors and windows to improve ventilation. Users can change settings in the app to test the possible effects of actions like these. For example, Figure 6 presents isothermal surface plots that show the effect that opening the AM machines' build chambers has on air temperature,

This story has been abridged.
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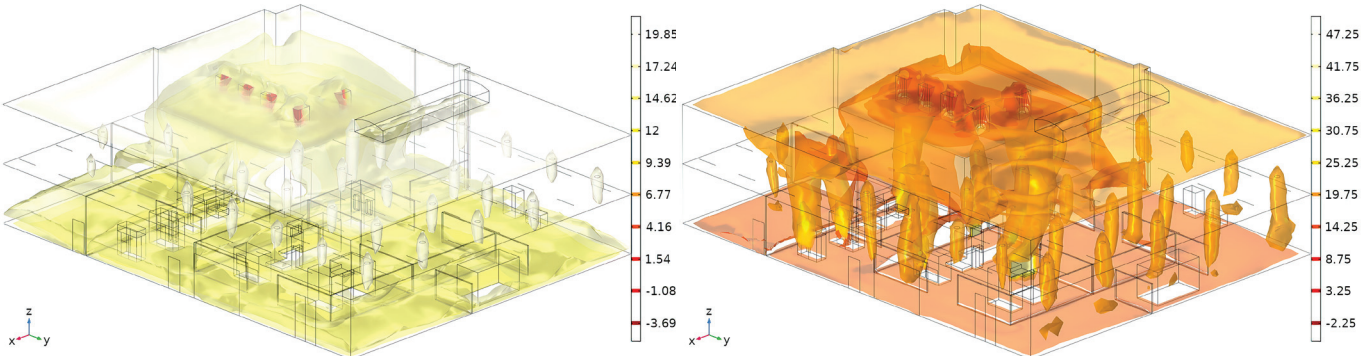


FIGURE 6 The simulation can capture variations in the thermal and fluid output of the machines over time. These isothermal surface plots show changes in temperature at 30 seconds (left) and 60 seconds (right) after opening the build chambers of every AM machine in the facility.

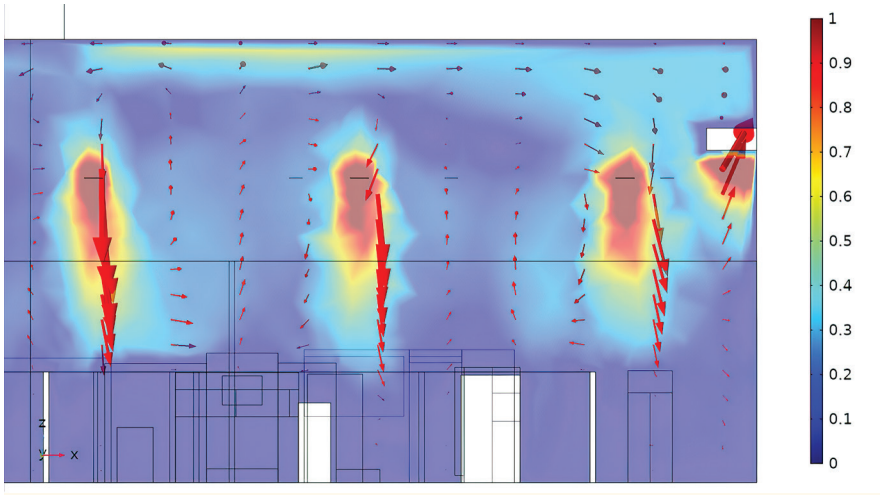


FIGURE 7 A slice plot showing the effect that opening a door has on airflow. Air velocity toward an outlet duct is significantly weakened when the door directly beneath it is opened.

while Figure 7 shows how airflow is affected by opening the facility doors.

» A STEP TOWARD A "FACTORY-LEVEL DIGITAL TWIN"

While the current app is an important step forward, it does still require workers to manually input relevant data. Looking ahead, the DRAMA team envisions something more integral, and therefore, more powerful: a "digital twin" for its AM facility. A digital twin, as described by Ed Fontes in a 2019 post on the COMSOL Blog, is "a dynamic, continuously updated representation of a real physical product, device, or process." It is important to note that even the most detailed model of a system is not necessarily its digital twin.

"To make our factory environment model a digital twin, we'd first provide it with ongoing live data from the actual factory," Holloway explains. "Once our factory model was running in the background, it could adjust its forecasts in response to its data feeds and suggesting specific actions based on those forecasts."

"We want to integrate our predictive model into a feedback loop that includes the actual factory and its staff. The goal is to have a holistic system that responds to current factory conditions, uses simulation to make predictions about future conditions, and seamlessly makes self-optimizing adjustments based on those predictions," Holloway says. "Then we could truly say we've built a digital twin for our factory."

» SIMULATION AT WORK ON THE FACTORY FLOOR

As an intermediate step toward building a full factory-level digital twin, the DRAMA simulation app has already proven its worth. "Our manufacturing partners may already see how modeling can help with planning an AM facility but not really understand how it can help with operation," Holloway says. "We're showing the value of enabling a line worker to open up the app, enter in a few readings or import sensor data, and then quickly get a meaningful forecast of how a batch of powder will behave that day."

Beyond its practical insights for manufacturers, the overall project may offer a broader lesson as well: By pairing its production line with a dynamic simulation model, the DRAMA project has made the entire operation safer, more productive, and more efficient. The DRAMA team has achieved this by deploying the model where it can do the most good — into the hands of the people working on the factory floor.

Workers inside the NCAM metal powder bed facility at MTC.

Exicom Tele-Systems, India

REFINING AUTOMOTIVE BATTERY MANAGEMENT SYSTEMS WITH LUMPED-APPROACH THERMAL MODELING

For India's transportation sector to meet its ambitious electrification goals, manufacturers must accelerate the development of essential components, such as battery management systems (BMS). Exicom optimizes BMS performance by using multiphysics simulation to understand the thermal behavior of different battery cell and pack designs.

by **NEENA PICARDO**

India is a fast-growing market for electric vehicles (EVs), with one study predicting that over 30% of the vehicles sold in India will be electric by 2030. The battery packs that power EVs are one of the main drivers of the electric mobility revolution in India. In order to monitor and manage battery pack performance and safety, packs are usually equipped with a battery management system (BMS). A BMS is an electronic system that monitors a battery's voltage, temperature, coolant flow, and health and predicts a number of other performance parameters, such as current variation and heat generation, helping to extract optimum performance from a battery pack.

» THE ROLE OF SIMULATION IN DEVELOPING ACCURATE BMS

Exicom Tele-Systems Pvt. Ltd. designs, develops, and deploys energy solutions, including the latest Li-ion battery technologies. To date, it has deployed Li-ion battery solutions totaling more than 1.8 GWh — among the highest in the world by a single company. Exicom also offers charging solutions and BMS for electric two-wheelers and light electric vehicles, which are driving the growth of electric mobility in India. Exicom's innovative BMS solutions are prized for their performance and life.

At Exicom's R&D center in Gurugram, India, the technology team led by Dr. Parmender Singh has developed a BMS that can be used to precisely monitor and manage Li-ion batteries in applications across a broad voltage range (up to 1000 V). This BMS is also chemistry agnostic; it can be used with Li-ion batteries of a range of chemistries such as lithium ferrophosphate, or lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA).

The precision of the BMS depends on the quality and accuracy of the inputs used for programming or calibrating the system. For example, the BMS includes a number of thermal sensors distributed across the battery pack. In order to accurately monitor a battery pack's temperature distribution and predict corresponding performance, it is imperative that the sensors be placed at the right locations. This requires a detailed understanding of the heat profile of each battery cell as well as how heat varies throughout the pack. This is where COMSOL Multiphysics® plays an integral part, by allowing for accurate computation and collation of the inputs, like heat profile information, that are required to develop a BMS with surgical precision.

» PREDICTING AND PREVENTING POTENTIAL THERMAL RUNAWAY

Dr. Singh's team at Exicom used COMSOL Multiphysics to perform a number of analyses on the thermal behavior of battery cells. They also used simulation to analyze potential external short circuits, which could cause thermal runaway — an uncontrolled self-heating

process that can damage equipment or even cause fires. The Exicom team began by analyzing the heat generated in cylindrical cells with different form factors and further extended this model to the pack level using the heat profile generated for the cells. "We were especially interested in improving the temperature gradient across the pack for air-cooled battery packs," said Dr. Singh.

The results for thermal modeling at the cell level for cylindrical cells during a 1C discharging are shown in Figure 1. The visualization on the left in Figure 1 shows the temperature distribution, where the maximum temperature is observed in the middle of the cell. The visualization on the right shows the contour distribution of temperature, where the maximum temperature is located in the active material of the cell.

The simulation results, when validated with experimental findings, were observed to be within the error limits of ±5% at the standard charge–discharge profile. The model was then further extended for 2C discharge at 100% state of charge (SOC) according to Standard UL1642, which is defined for external short-circuit testing.

The positive and negative terminals of the cell were shorted via an 80 ±20 mΩ resistance. The COMSOL® software's lumped approach-based thermal model was validated against experimental data for charge–discharge profiles of the cell. They also developed:

- Cyclic and calendric capacity-fade models for cylindrical cells based on the optimization features available in COMSOL®
- A high-fidelity pseudo two-dimensional (P2D) model for cylindrical cells using extracted electrochemical parameters

They found that the lumped approach enabled them to construct models using a minimal number of parameters — such as cell geometry, electrode thickness, thermal conductivity, heat capacity, drive cycle, and open-circuit voltage (OCV)-SOC table — that are readily available from battery pack manufacturers.

Extracting these parameters experimentally is not only a time-consuming process but also prone to errors due to variable experimental conditions. For example, ambient temperature fluctuates, so extracting an accurate heat profile of a cell requires performing an extensive series of tests at different ambient temperatures. Using simulation, however, Dr. Singh and the team were able to perform these experiments with great ease. They were able to efficiently study charge and discharge profiles, thermal behavior at different charge and discharge rates, and thermal runaway (Figure 2) due to external or internal short circuits for

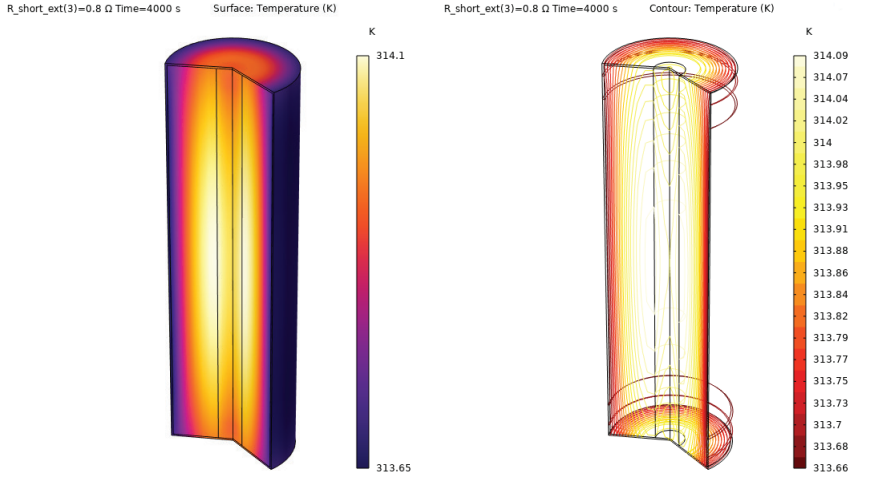


FIGURE 1 The temperature distribution in a cylindrical cell at 1C discharge (left) and the contour distribution of temperature (right).

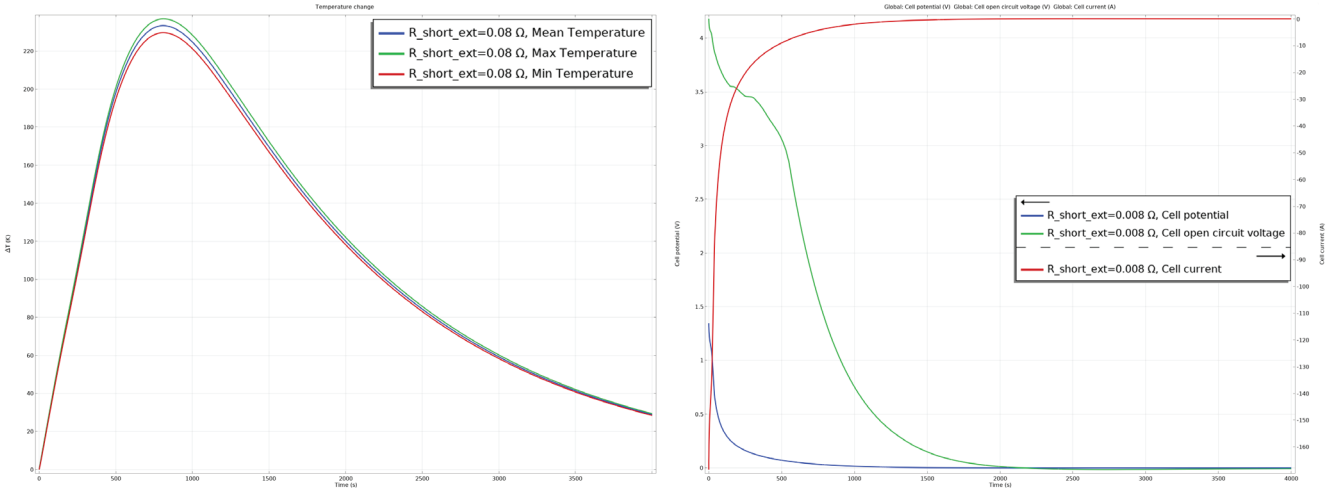


FIGURE 2 The temperature profile in a cell after thermal runaway (left) and the electrochemical profile in a cell after thermal runaway (right).

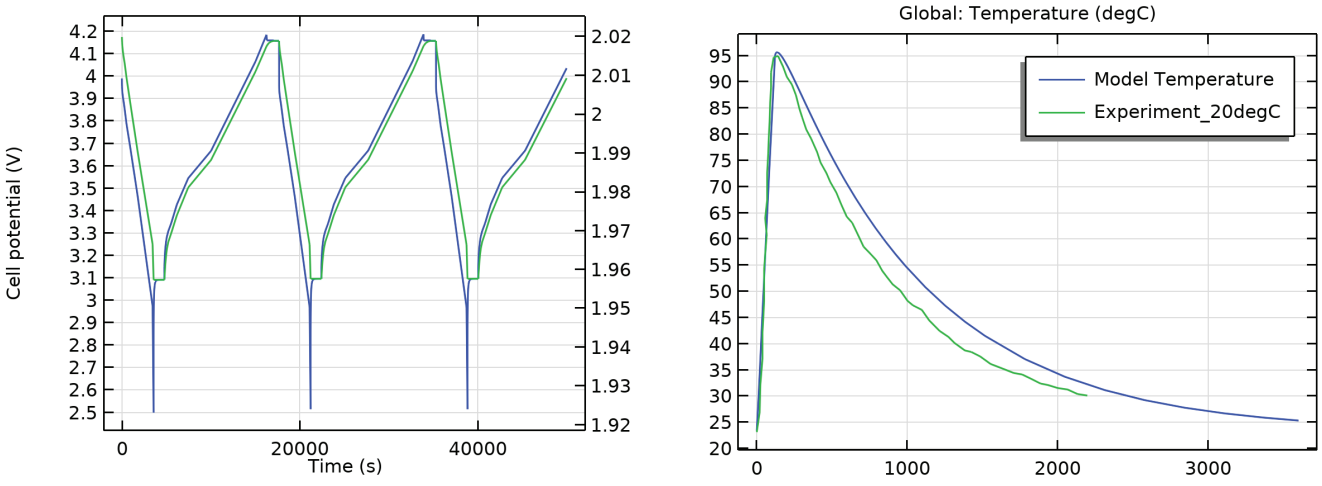


FIGURE 3 Simulated and experimental data during external short-circuit testing.

different cell chemistries (Figure 3). They were also able to identify the hotspots in the battery pack and determine the cell grading based on capacity fade analysis with high accuracy. These results had direct applications in reducing the development cycle time of the BMS, as the hotspots indicated the best positions for deploying the thermal sensors within the BMS in order to function most efficiently. According to Dr. Singh, "COMSOL® is an easy-to-learn and adaptable finite element tool for battery design and thermal modeling."

» FUTURE SCOPE: EXTENDING BATTERY SIMULATIONS TO PREDICT AGING

In addition to the thermal simulations, Dr. Singh has expanded the use of simulations to investigate another important phenomenon: battery aging. During the lifetime of a battery, its state of health (SOH) progressively deteriorates due to irreversible physical and chemical changes, such as the growth of a solid electrolyte interphase (SEI) layer, which can lead to loss of porosity in a battery cell, which in turn can lead to an increase in polarization and internal resistance. Magnetic field probing (MFP) is a noninvasive method for monitoring a battery's SOH. With the aim of demonstrating the potential of the MFP method, Dr. Singh developed a multiphysics model in COMSOL® to evaluate the magnetic field response, battery polarization, and internal resistance of the Li-ion response (Figure 4). The team observed that variation in electrode porosity has a significant influence on the magnetic field response. Though this research is currently in its preliminary stages, the potential applications are far reaching. "We expect that further investigation into this phenomenon will allow for developing and deploying monitoring features for battery aging as well as better protection mechanisms against it in the BMS itself," said Dr. Singh.

The Exicom team is currently working on electrochemical P2D modeling for thermal and capacity-fading analysis at the cell level. It intends to further extend the model with additional thermal exothermic equations at the electrodes and SEI layer for better accuracy during thermal runaway. They also plan to use the lumped capacity fade model for cyclic and calendric predictive analysis. In the future, they also plan to implement a reduced-order model for SOC and SOH and export the model to MATLAB® for code generation up to the ASIC level.

With the accelerating transition to electric mobility in India and worldwide, research on battery technology is expected to increase significantly in the coming years. Simulation software like COMSOL® offers a crucial head start to companies in the electric mobility space that want to provide more effective solutions and improve the time to market for their products. ◎

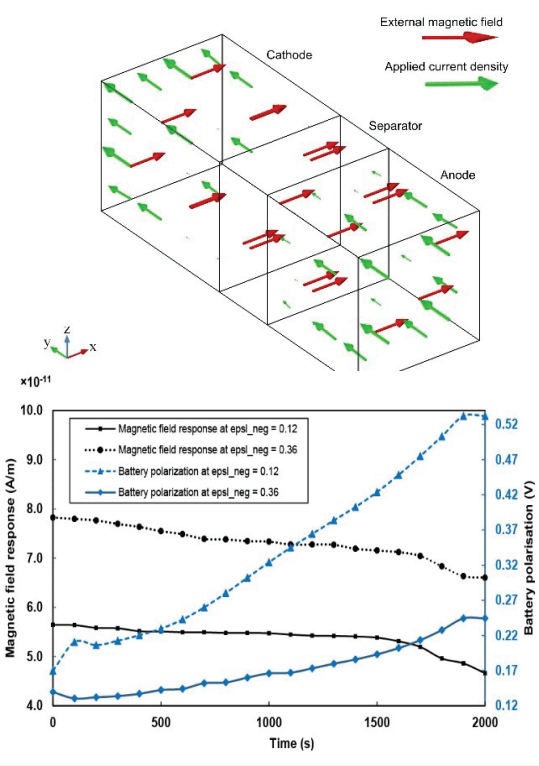


FIGURE 4 3D-designed cell geometry (top). Variation of magnetic field response and polarization behavior during discharging at 0.12 and 0.36 anode porosity values (bottom).

Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland

DESIGNING A SILICON PHOTONIC MEMS PHASE SHIFTER WITH SIMULATION

by **ALAN PETRILLO**

Optical fiber networks, which make up the backbone of the internet, rely on many electrical signal processing devices. Nanoscale silicon photonic network components, such as phase shifters, could boost optical network speed, capacity, and reliability. To design these small but powerful devices, a team at the Swiss Federal Institute of Technology Lausanne (EPFL) uses simulation to optimize both optical and electromechanical performance.

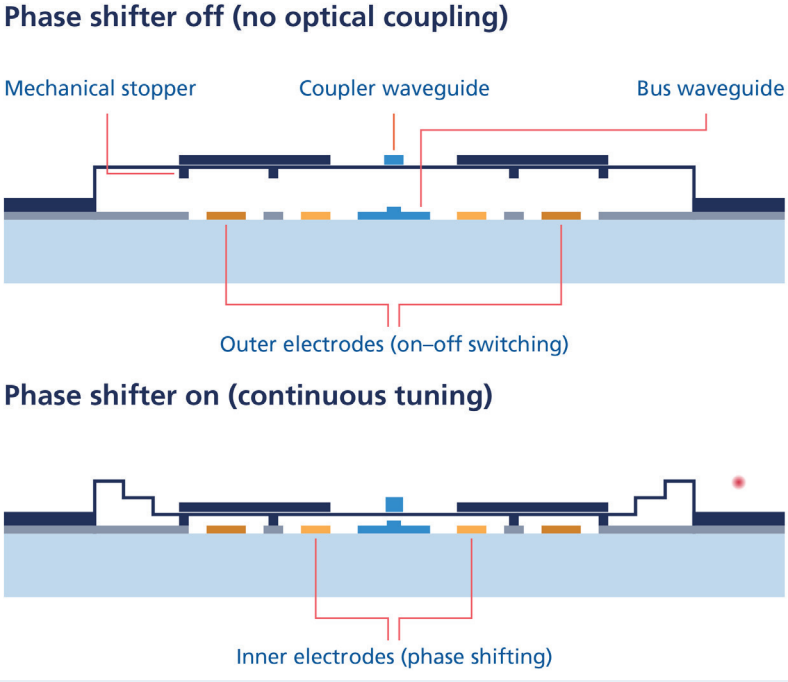


FIGURE 1 Two stages of motion for the MEMS mechanism in the phase shifter.

The modern internet-connected world is often described as *wired*, but most core network data traffic is actually carried by optical fiber — not electric wires. Despite this, existing infrastructure still relies on many electrical signal processing components embedded inside fiber optic networks. Replacing these components with photonic devices could boost network speed, capacity, and reliability. To help realize the potential of this emerging technology, a multinational team at the Swiss Federal Institute of Technology Lausanne (EPFL) has developed a prototype of a silicon photonic phase shifter, a device that could become an essential building block for the next generation of optical fiber data networks.

» LIGHTING A PATH TOWARD ALL-OPTICAL NETWORKS

Using photonic devices to process photonic signals seems logical, so why is this approach not already the norm? "A very good question, but actually a tricky one to answer!" says Hamed Sattari, an engineer currently at the Swiss Center for Electronics and Microtechnology (CSEM) specializing in photonic integrated circuits (PIC) with a focus on microelectromechanical system (MEMS) technology. Sattari was a key member of the EPFL photonics team that developed the silicon photonic phase shifter. In pursuing a MEMS-based approach to optical signal processing, Sattari and his colleagues are taking advantage of new and emerging fabrication technology. "Even ten years ago, we were not able to reliably produce integrated movable structures for use in these devices," Sattari says. "Now, silicon photonics and MEMS are becoming more achievable with the current manufacturing capabilities of the microelectronics industry. Our goal is to demonstrate how these capabilities can be used to transform optical fiber network infrastructure."

The phase shifter design project is part of EPFL's broader efforts to develop programmable photonic components for fiber optic data networks and space applications. These devices include switches; chip-to-fiber grating couplers; variable optical attenuators (VOAs); and phase shifters, which modulate optical signals. "Existing optical phase shifters for this application tend to be bulky, or they suffer from signal loss," Sattari says. "Our priority is to create a smaller phase shifter with lower loss, and to make it scalable for use in many network applications. MEMS actuation of movable waveguides could modulate an optical signal with low power consumption in a small footprint," he explains.

» HOW A MOVABLE WAVEGUIDE HELPS MODULATE OPTICAL SIGNALS

The MEMS phase shifter is a sophisticated mechanism with a deceptively simple-sounding purpose: It adjusts the speed of light. To shift the phase of light is to slow it down. When light is carrying a data signal, a change in its speed causes a change in the signal. Rapid and precise shifts in phase will thereby modulate the signal, supporting data transmission with minimal loss throughout the network. To change the phase of light traveling through an optical fiber conductor, or *bus waveguide*, the MEMS mechanism moves a piece of translucent silicon called a *coupler* into close proximity with the bus.

The design of the MEMS mechanism in the phase shifter provides two stages of motion (Figure 1). The first stage provides a simple on–off movement of the coupler waveguide, thereby engaging or disengaging the coupler to the bus. When the coupler is engaged, a finer range of motion is then provided by the second stage. This enables tuning of the gap between the coupler and bus, which provides precise modulation of phase change in the optical signal. "Moving the coupler toward the bus is what changes the phase of the signal,"

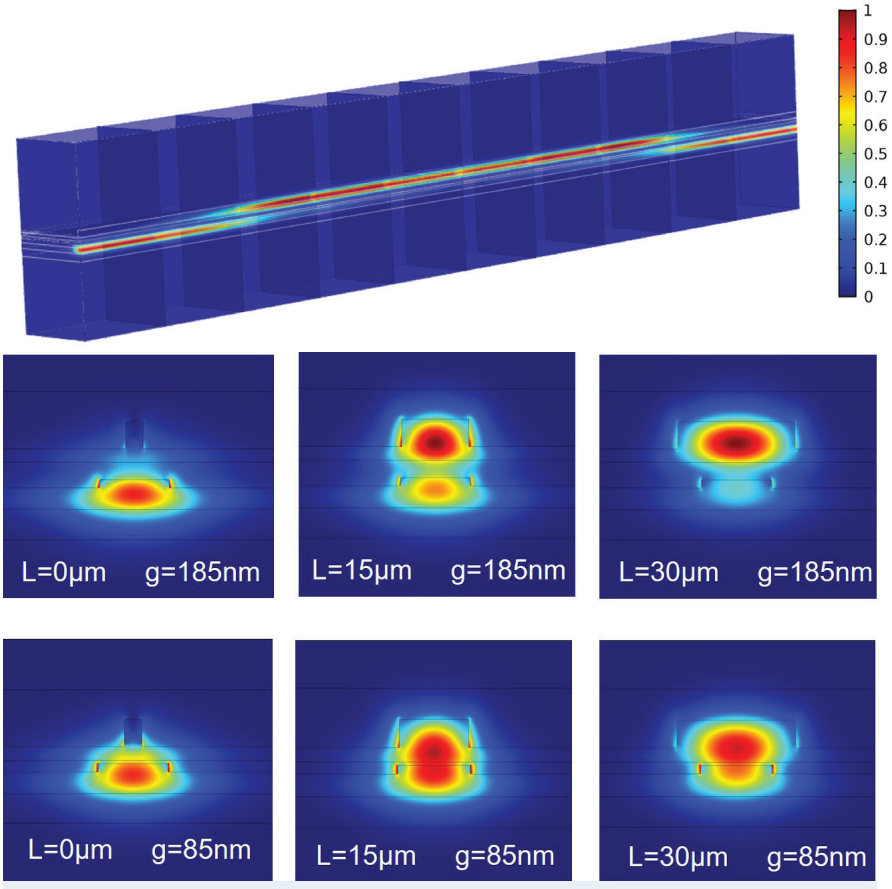


FIGURE 2 Top: Light passes from left to right through a path composed of an optical bus and a coupled movable waveguide. Bottom: six cross-sectional slices of a simulated light waveform as it passes through the coupled device. By adjusting the distance between the two optical elements in their simulation, the EPFL team could determine how that distance affected the speed, or phase, of the optical signal. Images courtesy EPFL and licensed under CC BY 4.0.

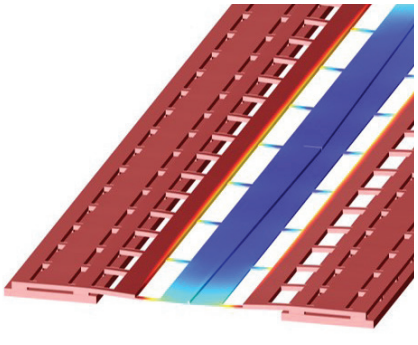


FIGURE 3 Simulation showing deformation of the movable waveguide support structure. The thin elements that suspend the movable waveguide will flex in response to an applied voltage. Image courtesy EPFL and licensed under CC BY 4.0.

explains Sattari. "The coupler is made from silicon with a high refractive index. When the two components are coupled, a light wave moving through the bus will also pass through the coupler, and the wave will slow down." If the optical coupling of the coupler and bus is not carefully controlled, the light's waveform can be distorted, potentially losing the signal — and the data.

» DESIGNING AT NANOSCALE WITH OPTICAL AND ELECTROMECHANICAL SIMULATION

The challenge for Sattari and his team was to design a nanoscale mechanism to control the coupling process as precisely and reliably as possible. As their phase shifter would use electric current to physically move an optical element, Sattari and the EPFL team took a two-track approach to the device's design. Their goal was to determine how much voltage had to be applied to the MEMS mechanism to induce a desired shift in the photonic signal. Simulation was an essential tool for determining the multiple values that would establish the voltage versus phase relationship. "Voltage vs. phase is a complex multiphysics question. The COMSOL Multiphysics® software gave us many options for breaking this large problem into smaller tasks," Sattari says. "We conducted our simulation in two parallel arcs, using the RF Module for optical modeling and the Structural Mechanics Module for electromechanical simulation."

The optical modeling (Figure 2) included a mode analysis, which determined the effective refractive index of the coupled waveguide elements, followed by a study of the signal propagation. "Our goal is for light to enter and exit our device with only the desired change in its phase," Sattari says. "To help achieve this, we can determine the eigenmode of our system in COMSOL®."

Along with determining the physical forms of the waveguide and actuation mechanism, simulation also enabled Sattari to study stress effects, such as unwanted deformation or displacement caused by repeated operation. "Every decision about the design is based on what the simulation showed us," he says.

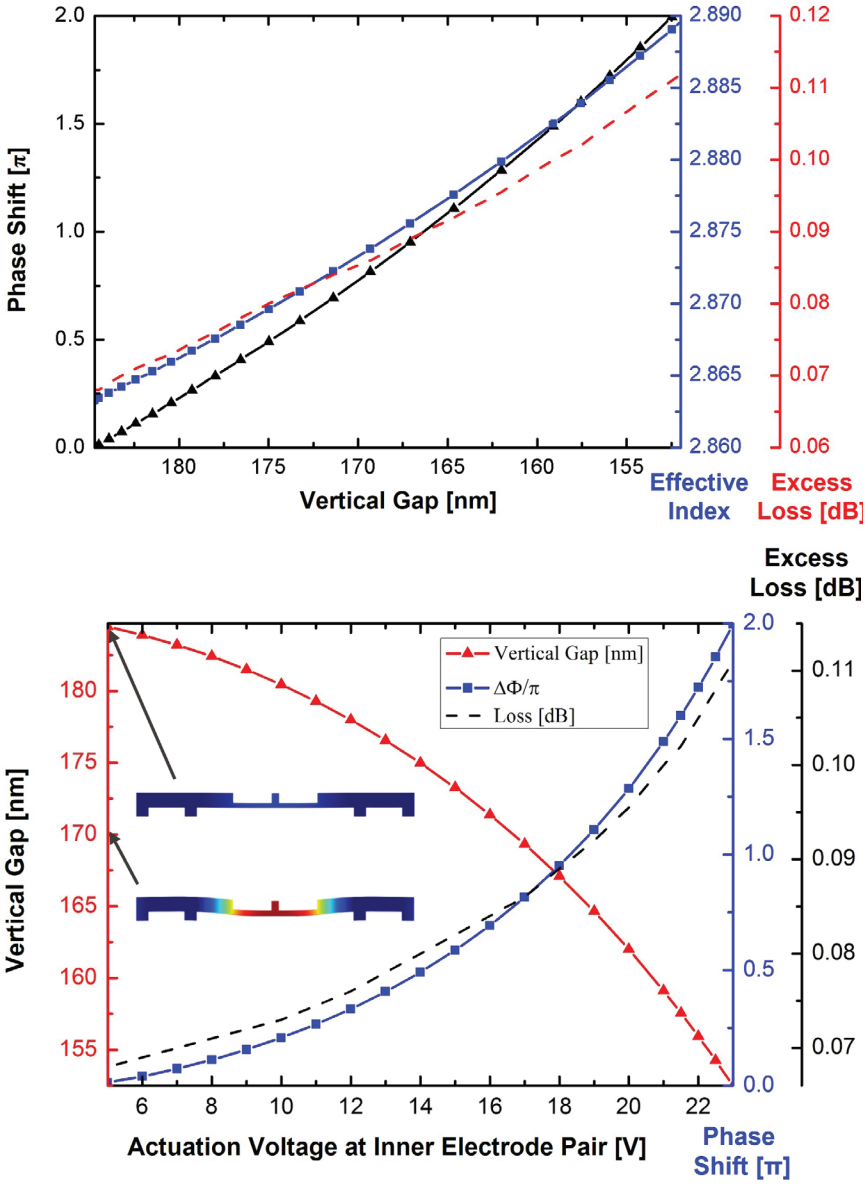


FIGURE 4 Optical simulation (top) established the vertical distance between the coupler and waveguide that would result in a desired phase shift in the optical signal. Electromechanical simulation (bottom) determined the voltage that, when applied to the MEMS mechanism, would move the coupler waveguide to the desired distance away from the bus. Images courtesy EPFL and licensed under CC BY 4.0.

» ADDING TO THE FOUNDATION OF FUTURE PHOTONIC NETWORKS

The goal of this project was to demonstrate how MEMS phase shifters could be produced with existing fabrication capabilities. The result is a robust and reliable design that is achievable with existing surface micromachined manufacturing processes, and occupies a total footprint of just 60 µm × 44 µm. Now that they have an established proof of concept, Sattari and his colleagues look forward to seeing their designs integrated into the world's optical data networks. "We are creating building blocks for the future, and it will be rewarding to see their potential become a reality," says Sattari.

Polar Night Energy, Finland

HEATING BUILDINGS WITH SOLAR ENERGY STORED IN SAND

by **ALAN PETRILLO**

Polar Night Energy, a startup in Finland, has developed technology for warming up buildings with solar-generated heat stored in sand. The team uses thermal modeling to optimize the design of their heat storage and distribution systems, which are helping Finnish cities reduce their consumption of nonrenewable heating fuels.

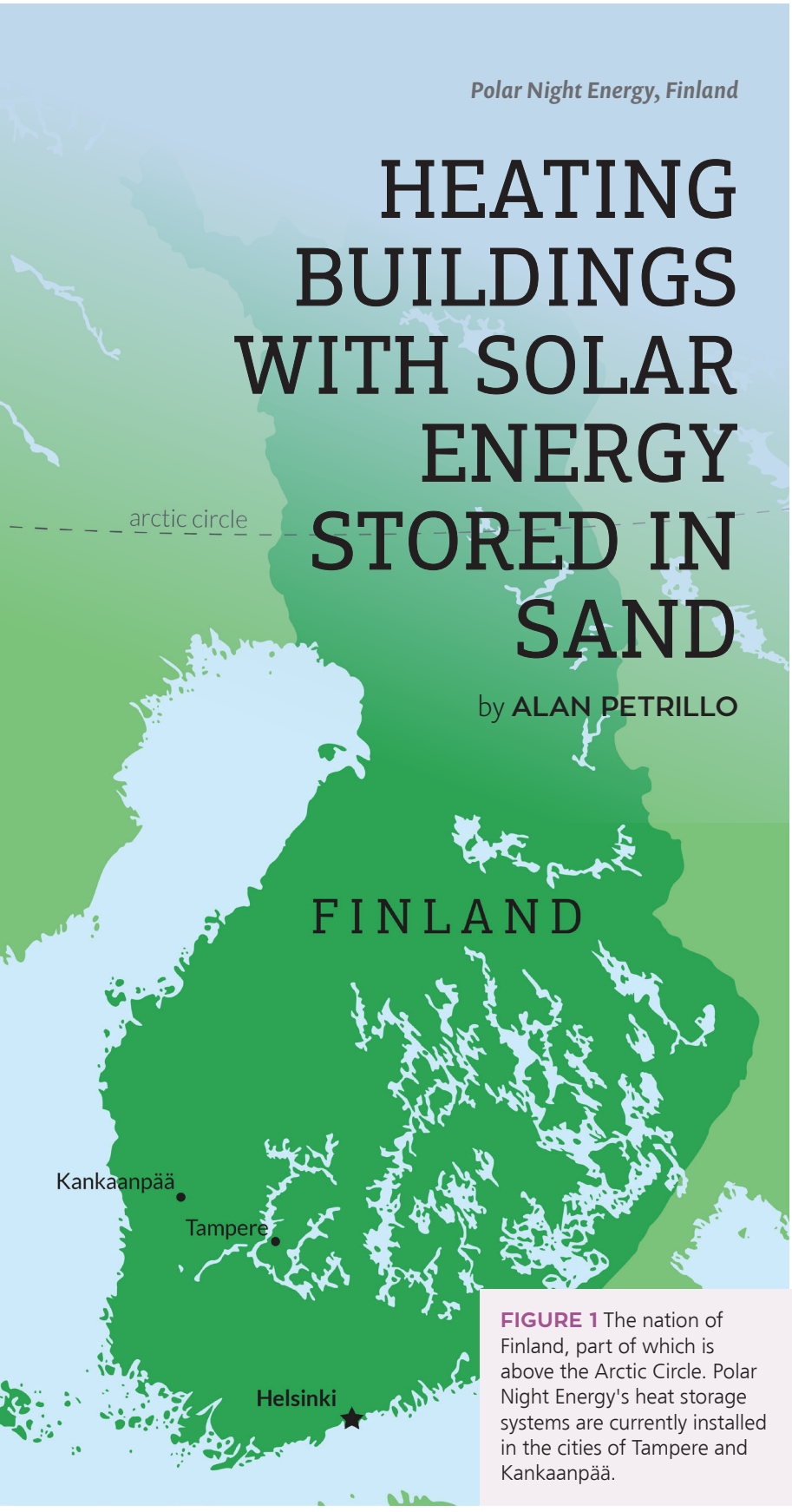


FIGURE 1 The nation of Finland, part of which is above the Arctic Circle. Polar Night Energy's heat storage systems are currently installed in the cities of Tampere and Kankaanpää.

As we try to objectively study nature, we are often reminded of how natural forces affect us personally. We can sit at a desk and consider heat in its various forms, but we might be distracted if our toes are cold! When we turn up the heat in our homes and workplaces, we must balance our personal need for warmth with the global impact of burning fossil fuels like oil, gas, coal, and biomass. Anthropogenic climate change confronts humanity with a challenge: How can we keep warm now as we try to prevent our world from overheating in the future?

It is a daunting question that a startup called Polar Night Energy, in the small and chilly nation of Finland (Figure 1), is attempting to answer. In a region known for long, dark winter nights, Polar Night Energy is building a system in the city of Tampere that can heat buildings with stored solar energy — all day, all night, and all winter long. The apparent

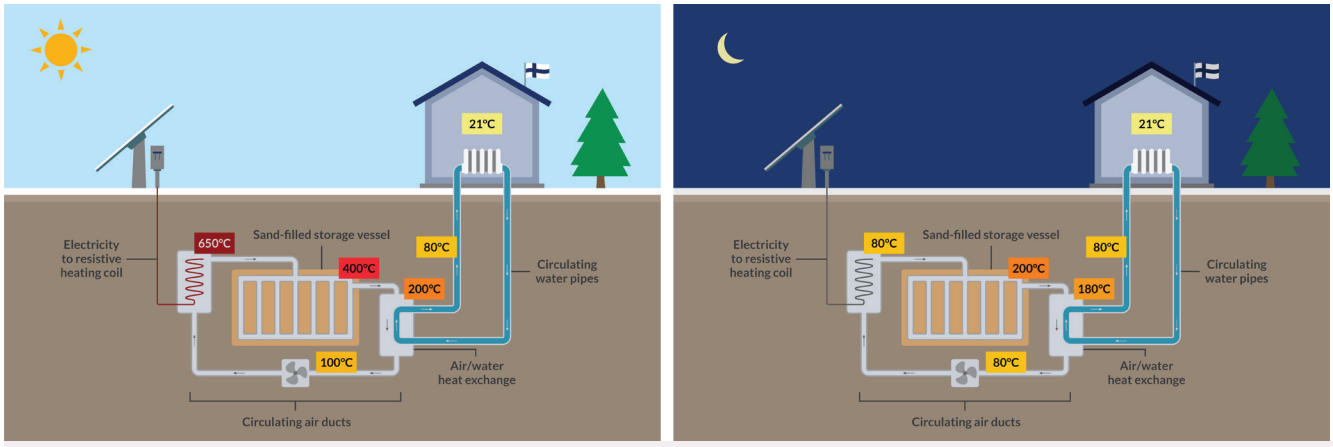


FIGURE 2 A schematic of the components and operating cycle of the Polar Night Energy system.

FIGURE 3 Markku Ylönen with a representative sample of Polar Night Energy's dirt-cheap heat storage medium.

FIGURE 4 Tommi Eronen (foreground) and Ylönen inspecting the ductwork of a Polar Night Energy heat storage vessel.

contradictions do not end there. In an era of complex cleantech solutions, often made from rare and expensive materials, Polar Night Energy's heat storage and distribution system consists of simple ducts, pumps, valves, and sand. The novel system shows potential for tackling global problems in a patient, thoughtful, and human-scaled way.

» A SMALL COUNTRY WITH LARGE HEATING NEEDS

Big problems demand big solutions, and there is perhaps no bigger 21st-century problem than climate change. To meet this challenge, many governments and organizations are investing in new technology to help lessen the use of fossil fuels. These initiatives have largely focused on renewable electric power generation, distribution, and storage.

"When you ask people about cleaner energy, they think of electricity," says Tommi Eronen, CEO of Polar Night Energy. "But we also have to cut emissions from heating." Out of Finland's energy-related emissions, 82% come from heating domestic buildings. "We want to replace all of that if we are to have any hope of meeting our global climate goals," Eronen says.

» THINK GLOBALLY, HEAT LOCALLY

The spirit of "Think Globally, Act Locally", a mantra associated with the 1960s, lives on with Polar Night Energy's team of innovators. Their journey began with a question posed by its founders, Tommi Eronen and Markku Ylönen, when they were university classmates: "Is it possible to build an energy-self-sufficient and cost-effective hippie commune for engineers using only solar power?" After graduation, the project they codenamed "Hippie Commune" became Polar Night Energy, with Eronen as CEO and Ylönen as CTO.

What began as a lighthearted (but serious) student project led to a 3 MWh/100 kW pilot plant in the Finnish city of Tampere, which began operation during the winter of 2020–2021. The system uses electricity to heat air, which is then circulated through an exchanger that heats water and distributes it to multiple buildings in the city's Hiedanranta district (Figure 2).

Inside the system, electrically powered resistive heating elements heat air to more than 600°C. The hot air is circulated through a network of pipes inside a sand-filled heat storage vessel. The hot air then flows

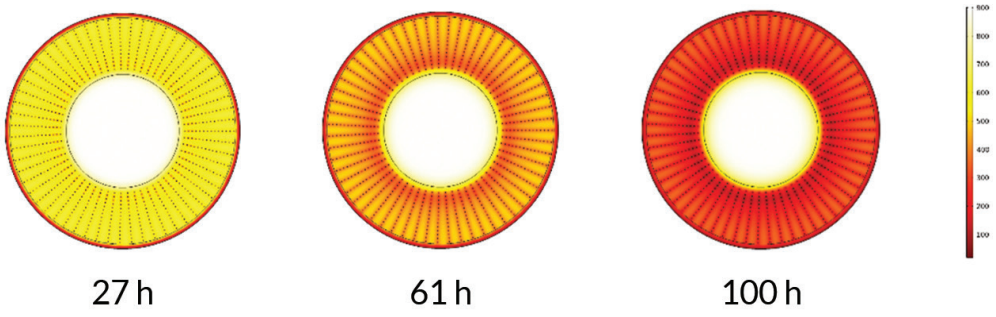


FIGURE 5 Simulation images showing temperature changes inside a proposed sand–air heat storage vessel design over a 100-hour period.

back out of the vessel into a heat exchanger, where it heats water that is then circulated through building heating systems. The sand's heat storage capacity ensures that even when the resistive elements are cool, the circulating air is still hot enough to keep the water (and buildings) warm.

"We only have pipes, valves, a fan, and an electric heating element. There is nothing special here!" Eronen says, laughing.

» A BATTERY FOR HEAT MADE FROM SAND

Noted chemical engineer Donald Sadoway is quoted as saying: "If you want to make a dirt-cheap battery, you have to make it out of dirt." Polar Night Energy's system faces the same core challenges as any other energy infrastructure. It must deliver power to people when they need it, where they need it, and at a manageable price. This means that storing and distributing energy is as important as its generation.

Existing infrastructure meets these challenges in familiar ways. For combustion-based heating, fuels like oil and gas are stored and moved to where they can be burned. The electrical grid also supports the efficient distribution of power and makes use of energy generated through renewable means like wind and solar. The intermittent nature of daylight and strong winds, however, is a stubborn problem. Energy storage is needed to maintain steady power output throughout the peaks and valleys of renewable inputs. But even with recent advances in battery technology, storing electric power remains relatively expensive, especially at the scale required for heating buildings. What if, rather than storing electricity, a "battery" could store heat instead?

Many conventional heating systems already store and distribute heat by retaining and circulating warm water. Eronen and Ylönen recognized the benefits of water-based heat storage as well as its limitations. "There is only so much heat you can add to water before it becomes steam," says Eronen. "Steam can efficiently distribute heat, but it is not really cost-effective for large-scale storage."

To avoid the drawbacks of storing heat in water, they instead turned to sand — 42 metric tons of it! (Figure 3) After the Sun goes down, the sand's stored heat is gradually released back into the circulating airflow. This keeps the air hot enough to maintain steady temperatures in the water that flows through customers' radiators. In this way, sand enables solar power to keep people warm, even during the darkest and coldest Finnish nights. "Sand provides four times the energy storage capacity of water," Eronen says. "Sand is efficient, nontoxic, portable, and cheap!"

"We need predictive modeling to answer as many questions as possible, before we commit to assembling all this equipment — and all this sand!"

— TOMMI ERONEN, CEO OF POLAR NIGHT ENERGY

» THE SOPHISTICATED ANALYSIS BEHIND A SIMPLE SOLUTION

Cost efficiency is the foundation of Polar Night Energy's value proposition. "As soon as we decided to pursue this idea, we were trying to figure out how the finances looked," says Eronen. In their quest to do more with less, Polar Night Energy has long depended on numerical simulation tools. Eronen and Ylönen began using the COMSOL Multiphysics® software as students, and it remains integral to their design process.

For example, Eronen mentions the specifications of an expanded heat storage system that would serve more buildings in Tampere. The team calculated that supplying heat to a district of 35,000 people would require a sand-filled storage cylinder that is 25 meters tall and 40 meters in diameter. How did they arrive at these dimensions? "The rough quantity of material needed is actually easy to calculate, because we know how much heat we can store in a cubic meter of sand," Eronen explains. "We also had to determine the space required for efficient heat transfer between the sand and our air circulating system (Figure 4). That is much more difficult to do! We used COMSOL® to model and evaluate different design options."

Multiphysics simulation software helped shape Polar Night Energy's heat exchanger design (Figures 5–6). Eronen says, "We built a particular model to explore a design idea: What if we created a super hot core of sand surrounded by heating ducts around the perimeter?" By modeling fluid flow and heat transfer effects in the COMSOL Multiphysics software, the Polar Night Energy team could quantify its design's comparative advantages and drawbacks. "The simulation confirmed that the 'hot core' design was good at storing heat for very long periods of time," says Eronen. "But for our intended operational cycle, it makes more sense to evenly distribute hot air ducts throughout the sand storage vessel," he explains.

The sheer scale of Polar Night Energy's sand-based heat storage system makes simulation software indispensable. "We cannot possibly build full-size

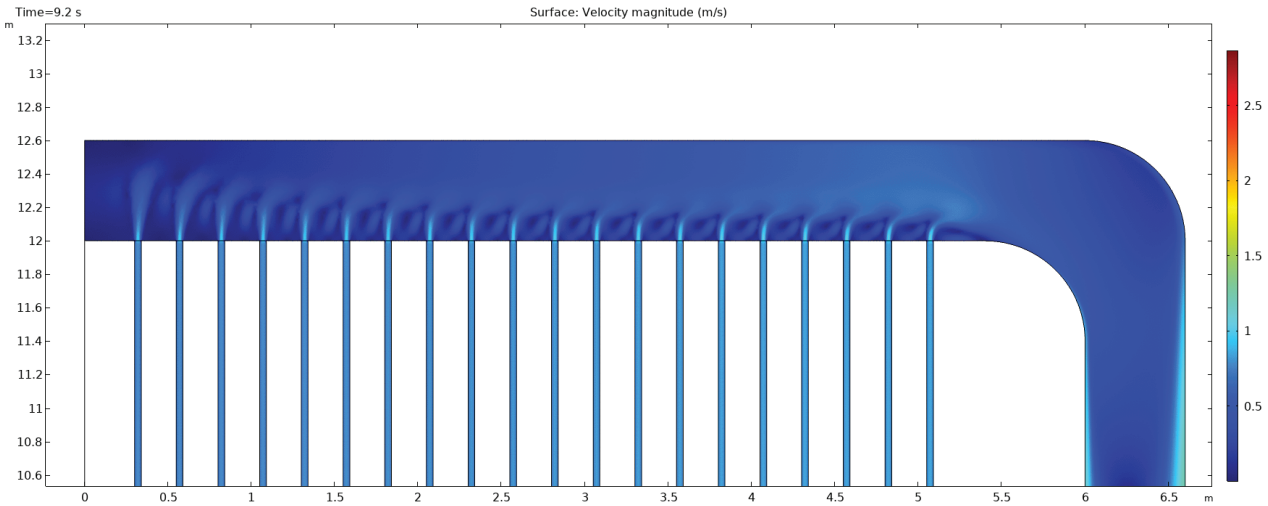


FIGURE 6 Simulation image of natural convection effects through ductwork inside the sand storage vessel.

FIGURE 7 Part of the heat transfer system installed by Polar Night Energy in Tampere, Finland. The vertical pipes at left are part of the heat exchanger, while the resistive heater elements are wrapped in white insulation at right. Between these components is the air-circulating radial blower.

prototypes to test all of our ideas. We need predictive modeling to answer as many questions as possible, before we commit to assembling all this equipment — and all this sand!" Eronen says. "It is essential for us to use these immensely powerful tools."

» ADAPTING NEW IDEAS TO EXISTING INFRASTRUCTURE

By separating the task of heat storage from heat generation and distribution, Polar Night Energy has made its system more efficient and adaptable. There is great potential for retrofitting their sand-filled heat storage and transfer systems into existing infrastructure (Figure 7).

Tampere, an inland Finnish industrial city of nearly 250,000 people, is an ideal testing ground for this new technology. "Tampere, like many European cities, already has a district heating system that circulates water across entire neighborhoods," says Eronen. "That enables us to switch many buildings to a renewable heat source quickly," he says. Polar Night Energy's pilot plant in Tampere can also tap into power from the existing electrical grid, along with electricity generated by new solar panels. Reliable thermal storage enables the city to generate or purchase power when it is most affordable and then distribute heat when it is needed most.

» TODAY: FINLAND; TOMORROW: THE WORLD

Since the Tampere system began operation during the winter of 2020–2021, the Polar Night Energy team has been gathering data to compare to their models. "Our simulations have proven to be very accurate, which is encouraging," Eronen says. And as the Polar Night Energy team continues to develop their ideas locally, they are aiming to act globally as well.

The same technology that warms Finland's long, chilly nights can also provide better energy management options to the rest of the world. Affordable thermal storage could help industries and cities capture heat that is currently wasted, as well as balance the inconsistencies in wind and solar power output. But while Polar Night Energy is eager to work directly with potential customers, they realize that the challenges ahead are too big for them to tackle alone.

"We want to license this technology. If you operate a power plant, please contact us," Eronen says with a laugh. On a more serious note, he adds, "We have to get away from all kinds of combustion, even biomass. We need to protect and restore forests so they can keep removing carbon from the air. Because climate change is happening so fast, we want our ideas to spread as quickly as possible." ◎

MED Institute, Indiana, USA

RADIOFREQUENCY-INDUCED HEATING OF MEDICAL DEVICES IN MRI SYSTEMS

Implanted medical devices in patients should be designed to be safe in and compatible with a magnetic resonance imaging (MRI) environment. MED Institute, a medical device contract research organization, is using computational modeling and simulation to analyze RF-heating of devices in MRI systems.

by **DIXITA PATEL**

Over 80 million magnetic resonance imaging (MRI) scans are conducted worldwide every year. MRI systems come in many different shapes and sizes, and are identified by their magnetic field strength. These scanners can range from below 0.55 tesla (T) to 3 T and beyond, where tesla is the unit for the static magnetic field strength. For patients with implanted metallic medical devices, the strong magnetic fields generated by MRI systems can pose several safety concerns.

For instance, high-powered magnets generate forces and torques that can cause the implant to migrate and potentially harm the patient. In addition, the gradient coils in MRI systems, used for spatial localization, can cause gradient-induced heating, vibrations, stimulation of the tissue, and device malfunction. Lastly, the large radiofrequency (RF) coil in MRI systems can cause the electrically conductive implant to electromagnetically resonate (called the "antenna effect"), resulting in RF-induced heating that can potentially burn the patient.

MED Institute, a full-service contract research organization (CRO) for the medical device industry, is using multiphysics simulation to better understand the effects of RF-induced heating of medically implanted devices for patients that need MRI scans.

» STANDARDIZED TEST METHODS FOR MEDICAL DEVICES

MED Institute provides support throughout the entire product development cycle. Its MRI Safety team helps manufacturers evaluate and perform physical testing of their medical devices for safety and compliance in the MRI environment (Figure 1). The team works closely with the Food and Drug Administration (FDA), which oversees the development of medical products to ensure safe and effective use. Furthermore, the team complies with the standards of the American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO). Specifically, it follows the ASTM F2182 standard to measure RF-induced heating of a medical implant within a gel phantom (Figure 2) and follows ISO/TS 10974 to evaluate electrically active implantable medical devices (AIMD) during MRI.

The gel phantom used for testing is a rectangular acrylic container filled with a conductive gel that approximates the thermal and electrical properties of average human tissue. The phantom is placed on the patient table inside the RF coil of an MRI scanner and fiber optic temperature probes (1 mm in diameter) are attached to the device before submerging it into the gel. The probes measure the temperature changes experienced by the device during the MRI scan. This type of physical experiment is used often, but it poses some potential problems. For instance, movement within the phantom can introduce uncertainty into the experiment, and inaccurate probe placement can lead to invalid results. In addition, depending on the materials of construction and their magnetic susceptibility, magnetic force could also be an issue.

To help address these issues, the team at MED Institute uses computational modeling and simulation as an alternative to physical testing. David Gross, PhD, PE, Director of MRI Safety

FIGURE 1 Engineers at MED Institute Inc. performing physical MRI testing to evaluate the safety of medical devices in the MRI environment.

Evaluations and Engineering Simulations, leads a team of analysts that use simulation to gain a better understanding of physics-based problems. He says, "The simulation provides us with 3D temperature contours anywhere within a volume of interest; we are not limited to discrete point-probe measurements, and we do not have to worry about the inaccuracies of the equipment or uncertainty of probe placement from the experiment."

The team has experience conducting these simulations for closed-bore MRI systems, in which a patient is contained in a compact tube. The team is now using simulation to perform these same analyses for open-bore systems (Figure 3), which have wider physical access, making them beneficial for "imaging pediatric, bariatric, geriatric and claustrophobic patients", as is explained on the MED Institute website.

» MULTIPHYSICS SIMULATION FOR RF-INDUCED HEATING

With COMSOL Multiphysics®, MED Institute is able to evaluate the RF-induced temperature rise of implants and compare the results of various sizes and constructs of a device within a product family to determine a worst-case configuration. The analysts at MED can import a CAD file of a client's device using the CAD Import Module, an add-on to COMSOL Multiphysics. In terms of RF-induced heating, the team uses the RF Module and Heat Transfer Module add-on products to combine the physics of electromagnetics with transient heat transfer. For analyzing electromagnetics,

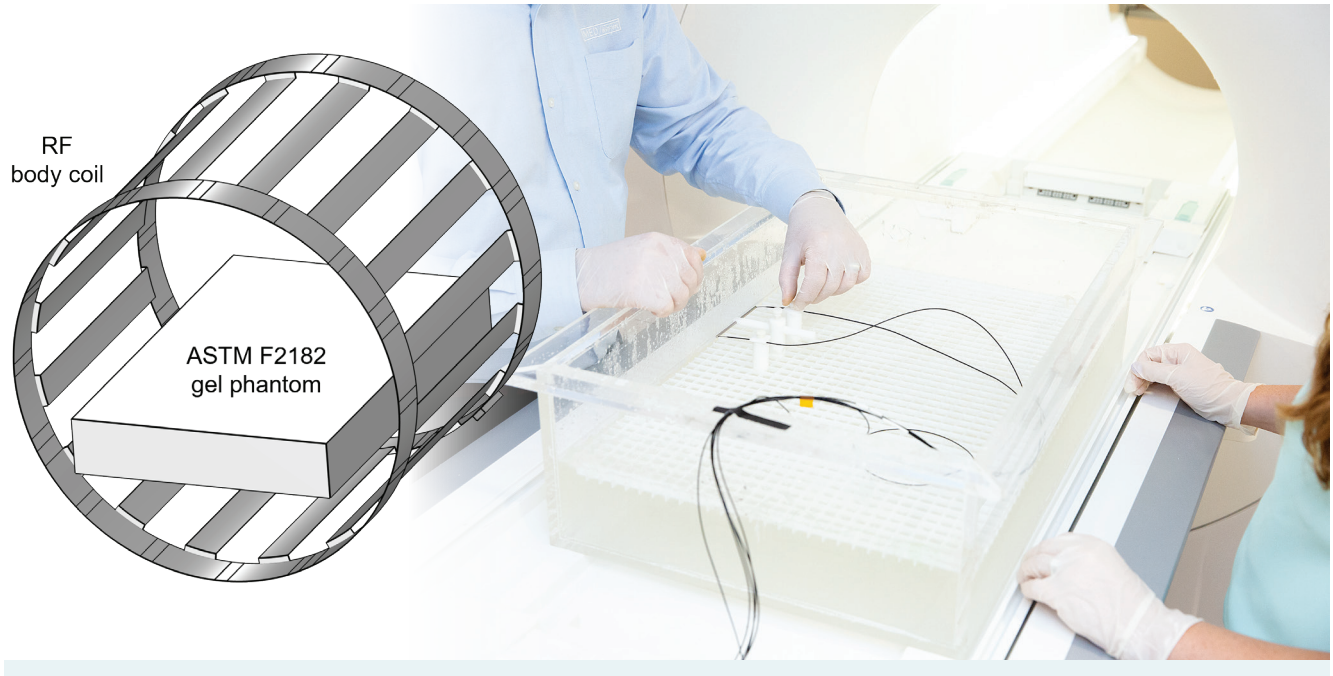


FIGURE 2 The ASTM F2182 standard used under virtual testing (left) and during physical testing under an MRI (right).

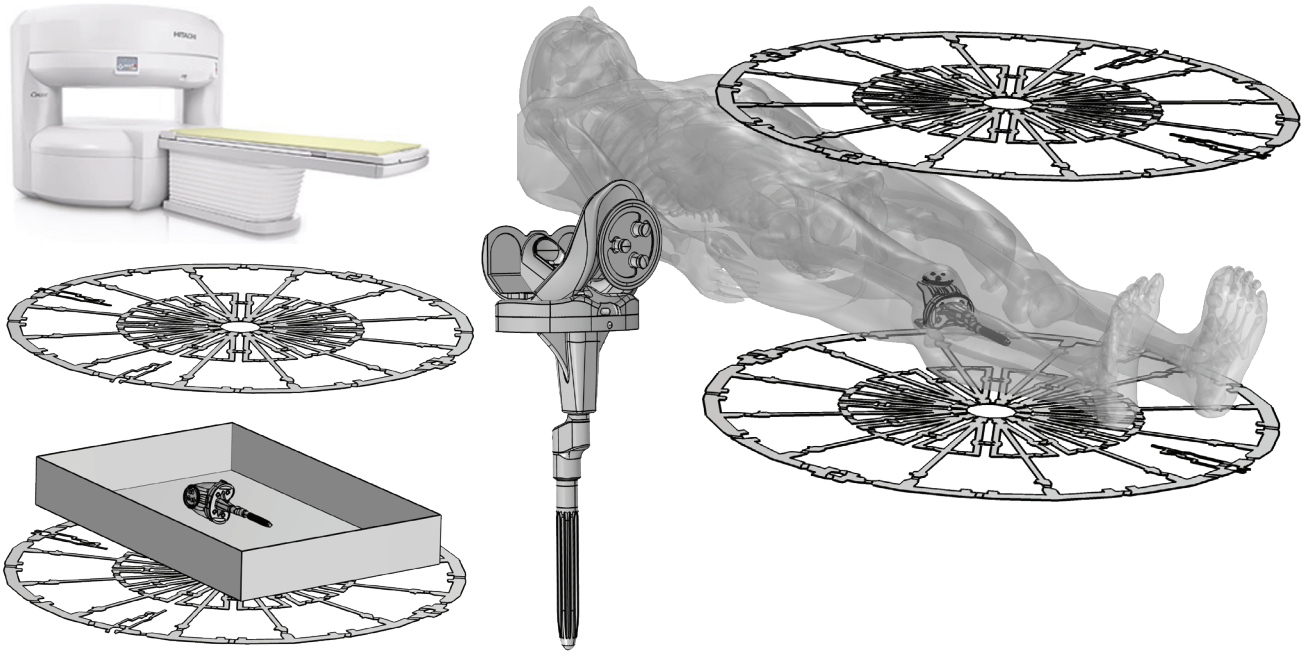


FIGURE 3 An open-bore MRI system (top left), an RF body coil with the IT'IS Foundation's Duke virtual human model (top right), an RF body coil of a knee implant in an ASTM gel phantom (bottom left), and CAD model of a knee implant (bottom center).

the RF Module enables the use of Maxwell's equations to solve for the wave equation at every point within the model that is impacted by electromagnetic fields. This is done in a steady-state frequency domain, which is then sequentially coupled with the transient heat transfer. With the Heat Transfer Module, the team is also able to solve heat conduction equations.

In the example below, MED Institute imported a CAD file of a knee implant into the COMSOL Multiphysics software. The geometry of the implant included a stem extension, tibial tray, femoral tray, and other components. All of these components can have various sizes and can be assembled in various ways, and patients with the implant can be scanned in various MRI systems that create different electromagnetic fields. With the overwhelming amount of permutations that these variables can produce, it is often not clear which configuration would result in the worst-case RF-induced heating.

"This is where the use of simulation comes in; you focus your efforts on the primary factors that can change the resonance of a particular implant," Gross says. By using the COMSOL® software, the organization is able to better understand the relative bounds of where it would expect to see resonance and how the device behaves under different electromagnetic fields. This helps with performing sensitivity analyses, where the team can test what causes the change in resonance, such as modifying the diameter of the stem or other components of the implant. For this particular case, the team ran hundreds of simulations to determine the worst-case device size and worst-case RF frequency.

Using worst-case analysis is crucial in the verification process because it allows manufacturers to test different factors for a wide range of devices — such as determining which size brings the most complications — rather than conducting physical testing for every variant of one product. "Performing multiple physical experiments becomes very expensive and time-consuming, especially when you account for the hourly cost of using a physical MRI scanner," says Gross.

As shown in Figure 4, the electric field in the gel phantom of a 1.2 T open-bore system (upper left) is very different from a 1.5 T closed-bore system (upper right). The knee implant was simulated in both systems, where the results show a different resonance and maximum temperature rise at the end of the stem (lower images).

Using COMSOL® allowed the team to better understand how a device behaves under electromagnetic fields. With these results, the team was then able to determine where the temperature probes should be placed while physically testing the device in an actual MRI system to obtain temperature rise results.

» FDA QUALIFICATION OF MED INSTITUTE'S VIRTUAL MRI SAFETY EVALUATIONS

MED Institute's experience with using simulation to test RF-induced heating of medical devices has inspired development of a promising new simulation tool that accelerates the product development cycle. The MED Institute team submitted this simulation tool to the FDA's Medical Device Development Tool (MDDT) program, which allows the FDA to evaluate new tools with the purpose of furthering medical products and studies. As stated on the FDA website, "The MDDT program is a way for the FDA to qualify tools that medical device sponsors can choose to use in the development and evaluation of medical devices." Once qualified, the FDA recognizes the tool as an official MDDT.

In November 2021, MED Institute was granted FDA

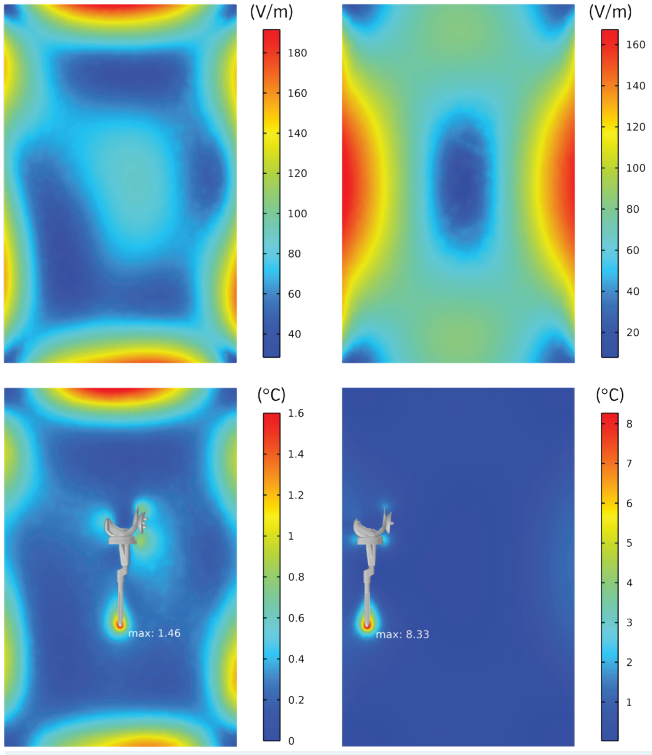


FIGURE 4 A knee implant in a gel phantom comparing the simulation results of an open-bore (left) and closed-bore (right) system.

qualification of its MDDT, "Virtual MRI Safety Evaluations of Medical Devices". This is an evaluation process that involves using multiphysics modeling and simulation to test the interactions of medical devices in an MRI environment. The tool is used for modeling an RF coil of an MRI system, ASTM gel phantom, and a medical device placed within the gel. Simulation is then used to analyze the electromagnetics and the heat that generates around the device.

After testing is complete, the labeling of the device is described by ASTM 2503 or, if it is an electrically active implant, by the ISO 10974 test. The labeling is placed on the device packaging and inside the instructions for use (IFU) so that an MRI technologist or radiologist can see the relevant information for a patient with an implanted device.

"With our MDDT, we can not only augment physical testing but even replace it with simulation in some cases," says Gross.

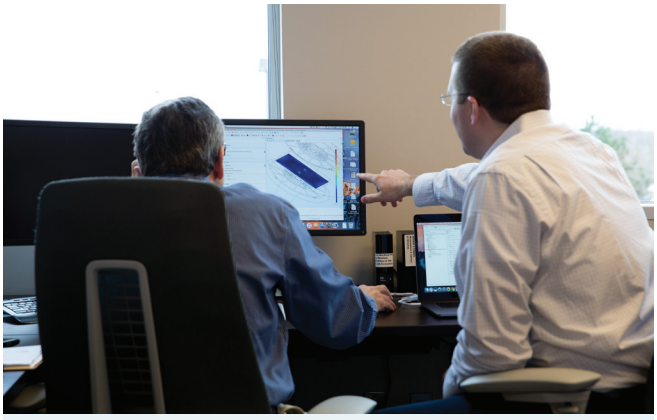
» MODELING AND SIMULATION SUPPORT FROM THE FDA

Over the years, MED Institute has evaluated many medical devices for MRI safety with COMSOL Multiphysics simulations. It has found that COMSOL® is a powerful and efficient platform for solving complex multiphysics problems. "The immediate, positive results are that our clients are able to have their products evaluated quicker and at less cost because we are able to rely on the simulation. It does not require them to send us the actual product to test for RF-induced heating," says Gross.

The FDA has been supportive of computational modeling and is willing to evaluate and accept data from simulation in lieu of physical testing. "It is important for medical device sponsors to know that they have the encouragement and support of the FDA," Gross says. MED Institute has had the privilege of working alongside the FDA for many years for the benefit of patients. "It goes to show that they are invested and believe in the power of modeling and simulation," Gross adds.

"With our Medical Device Development Tool (MDDT), we can not only augment physical testing but even replace it with simulation in some cases. The immediate, positive results are that our clients are able to have their products evaluated quicker and at less cost because we are able to rely on the simulation."

— DAVID GROSS, MED INSTITUTE DIRECTOR OF MRI SAFETY EVALUATIONS AND ENGINEERING SIMULATIONS



MED Institute uses the COMSOL Multiphysics software to accelerate the product development cycle for its clients.

Eden Tech, France

DESIGNING A MINIATURIZED WASTEWATER TREATMENT PLANT FOR MICROPOLLUTANT DEGRADATION

Micropollutants are added to the world's lakes, rivers, and streams every day. Many conventional wastewater treatment plants are not equipped to remove these potentially hazardous chemical residues from wastewater. Eden Tech, a deeptech company based in Paris, France, is using multiphysics simulation to develop a device that can help with this emerging problem.

by **RACHEL KEATLEY**

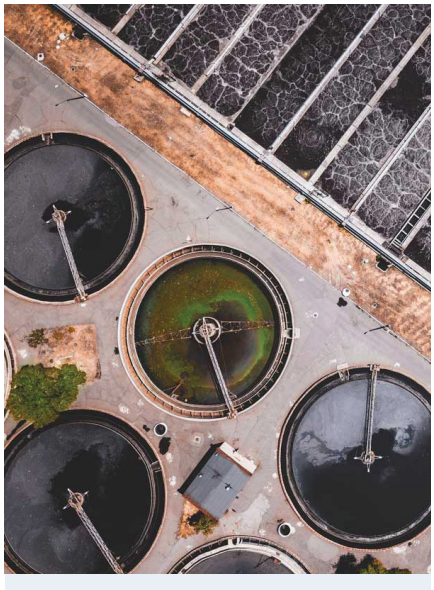


FIGURE 1 Most conventional water treatment plants are not able to remove micropollutants.

The 1985 action-adventure TV series *MacGyver*® showcased the life of Angus MacGyver, a secret agent who solved problems using items he had on hand. For example, in one episode, he made a heat shield out of used refrigerator parts. In another, he made a fishing lure with a candy wrapper. More than three decades later, the show still has relevance. The verb *MacGyver*, to design something in a makeshift or creative way, was added to the Oxford English Dictionary in 2015.

Try putting your MacGyver skills to the test: If you were handed some CDs, what would you make out of them? Reflective wall art, mosaic ornaments, or a wind chime, perhaps? What about a miniaturized water treatment plant?

This is what a team of engineers and researchers is doing at Eden Tech, a company that specializes in the development of microfluidics technology. Eden Tech's R&D department, Eden Cleantech, is developing a compact, energy-saving water treatment system to help tackle the growing presence of micropollutants in wastewater. To analyze the performance of its AKVO system (named after the Latin word for water, *aqua*), which is made from CDs, Eden Tech turned to multiphysics simulation.

» CONTAMINANTS OF EMERGING CONCERN

"There are many ways micropollutants make it into wastewater," says Wei Zhao, a senior chemical engineer and chief product officer at Eden Tech. The rise of these microscopic chemicals in wastewater worldwide is a result of daily human activities. For instance, when we wash our hands with soap, wipe down our sinks with cleaning supplies, or flush medications out of our bodies, various chemicals are washed down the drain and end up in sewage systems. Some of these chemicals are classified

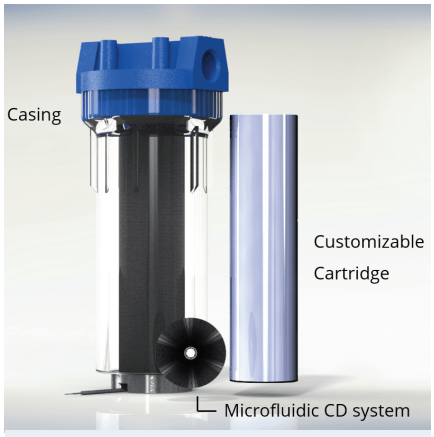


FIGURE 2 AKVO, with all of its components labeled.

as micropollutants, or contaminants of emerging concern (CECs). In addition to domestic waste, agricultural pollution and industrial waste are also to blame for the rise of micropollutants in our waterways.

Unfortunately, many conventional wastewater treatment plants (Figure 1) are not designed to remove these contaminants. Therefore, they are often reintroduced to various bodies of water, including rivers, streams, lakes, and even drinking water. Although the risk they pose to human and environmental health is not fully understood, the increasing amount of pollution found in the world's bodies of water is of concern.

With this growing problem in mind, Eden Tech got to work on developing a solution, and AKVO was born. One AKVO cartridge is composed of stacked CDs of varying numbers, combined to create a miniaturized factory. Each AKVO CD core is designed to have a diameter of 15 cm and a thickness of 2 mm. One AKVO core treats 0.5 to 2 m^3 water/day, which means that an AKVO system composed of 10,000 CDs can treat average municipal needs. This raises the question: How can a device made from CDs decontaminate water?

» A SUSTAINABLE WASTEWATER TREATMENT METHOD

A single AKVO system (Figure 2) consists of a customizable cartridge filled with stacked CDs that each have a microchannel network inscribed on them. It removes undesirable elements in wastewater, like micropollutants, by circulating the water in its microchannel networks. These networks are energy savvy because they only require a small pump to circulate and clean large volumes of water. The AKVO system's cartridges can easily be replaced, with Eden Tech taking care of their recycling.

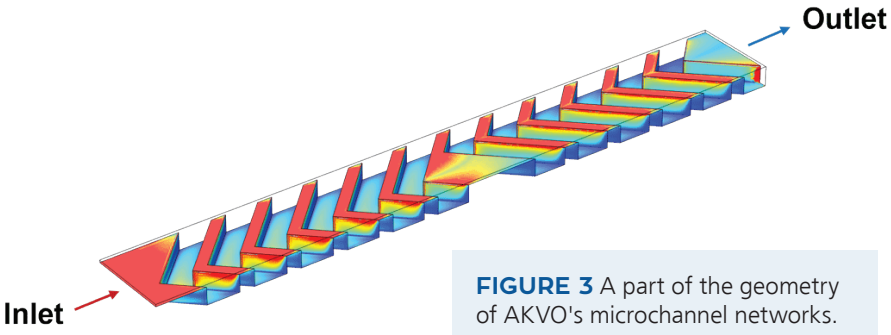


FIGURE 3 A part of the geometry of AKVO's microchannel networks.

AKVO's revolutionary design combines photocatalysis and microfluidics into one compact system. Photocatalysis, a type of advanced oxidation process (AOP), is a fast and effective way to remove micropollutants from wastewater. Compared to other AOPs, it is considered safer and more sustainable because it is powered by a light source. During photocatalysis, light is absorbed by photocatalysts that have the ability to create electron-hole pairs, which generate free hydroxyl radicals that are able to react with target pollutants and degrade them. Combining photocatalysis and microfluidics for the treatment of wastewater has never been done before. "It is a very ambitious project," said Zhao. "We wanted to develop an innovative method in order to provide an environmentally friendly, efficient way to treat wastewater." AKVO's current design did not come easily, as Zhao and his team faced several design challenges along the way.

» OVERCOMING DESIGN CHALLENGES

When in use, a chemical agent (catalyst) and wastewater are dispersed through AKVO's microchannel walls. The purpose of the catalyst, titanium dioxide in this case, is to react with the micropollutants and help remove them in the process. However, AKVO's fast flow rate complicates this action. "The big problem is that [AKVO] has microchannels with fast flow rates, and sometimes when we put the chemical agent inside one of the channels' walls, the micropollutants in the wastewater cannot react efficiently with

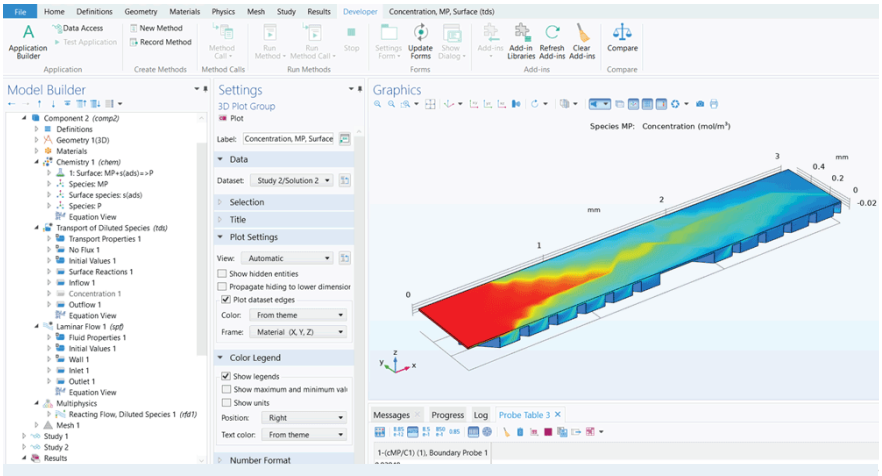


FIGURE 4 In COMSOL Multiphysics®, Zhao used the *Chemistry*, *Transport of Diluted Species*, *Laminar Flow*, and *Reacting Flow, Diluted Species* interfaces.

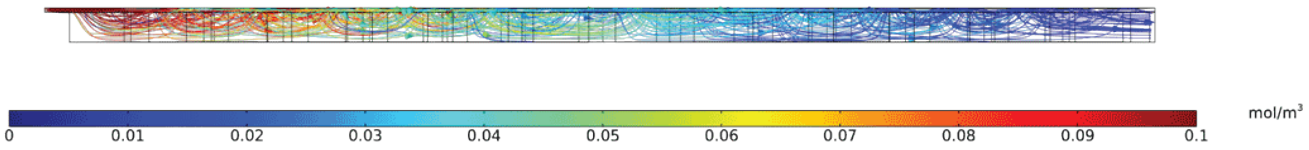


FIGURE 5 Results of the Explicit Surface Adsorption model.

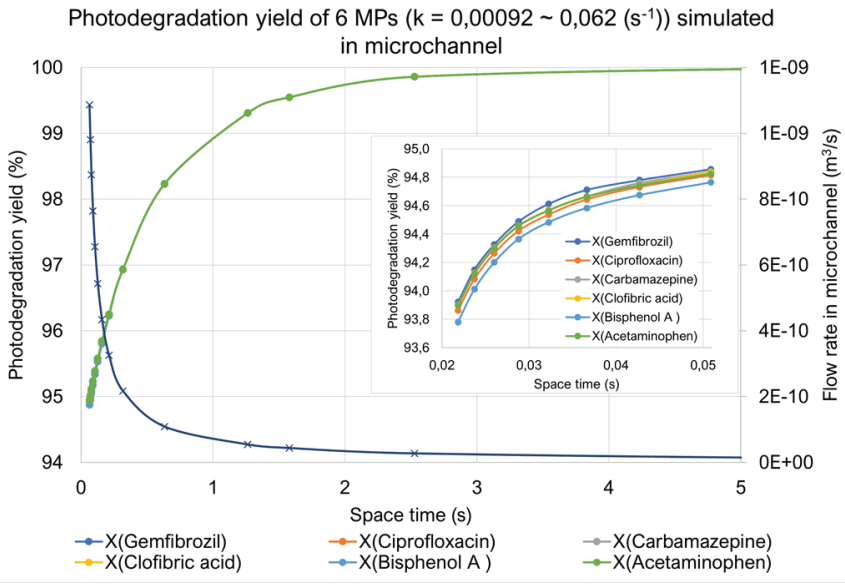


FIGURE 6 Comparison of the performance of the SHM design for the photodegradation of six different micropollutants.

the agent," said Zhao. In order to increase the opportunity of contact between the micropollutants and the immobilized chemical agent, Zhao and his team opted to use a staggered herringbone micromixer (SHM) design for AKVO's microchannel networks (Figure 3).

To analyze the performance of the SHM design to support chemical reactions for micropollutant degradation, Zhao used the COMSOL Multiphysics software.

» SIMULATING CHEMICAL REACTIONS FOR MICROPOLLUTANT DEGRADATION

In his work, Zhao built two different models in COMSOL Multiphysics (Figure 4), named the Explicit Surface Adsorption (ESA) model and the Converted Surface Concentration (CSC) model. Both of these models account for chemical and fluid phenomena.

In both models, Zhao found that AKVO's SHM structure creates vortices in the flow moving through it, which enables the micropollutants and the chemical agent to have a longer reaction period and enhances the mass transfer between each fluid layer. However, the results of the ESA model (Figure 5) showed that the design purified about 50% of the micropollutants under treatment, fewer than what Zhao expected.

Unlike the ESA model, in the CSC model, it is assumed that there is no adsorption limitation. Therefore, as long as a micropollutant arrives at the surface of a catalyst, a reaction occurs, which has been discussed in existing literature. In this model, Zhao analyzed how the design performed for the degradation of six different micropollutants, including gemfibrozil, ciprofloxacin, carbamazepine, clofibric acid, bisphenol A, and acetaminophen (Figure 6). The results of this model were in line with what Zhao expected, with more than 95% of the micropollutants being treated.

"We are really satisfied with the results of COMSOL Multiphysics. My next steps will be focused on laboratory testing [of the AKVO prototype]," said Zhao. The prototype will eventually be tested at hospitals and water treatment stations in the south of France.

Using simulation for this project has helped the Eden Tech team save time and money. Developing a prototype of a microfluidic system, like AKVO, is costly. To imprint microchannel networks on each of AKVO's CDs, a microchannel photomask is needed. According to Zhao, to fabricate one photomask would cost about €3000 (3500 USD). Therefore, it is very important that they are confident that their system works well prior to its fabrication. "COMSOL Multiphysics has really helped us validate our models and our designs," said Zhao.

» PIONEER IN THE TREATMENT OF MICROPOLLUTANTS

In 2016, Switzerland introduced legislation mandating that wastewater treatment plants remove micropollutants from wastewater. Its goal? Filter out over 80% of micropollutants at more than 100 Swiss facilities. Following Switzerland's lead, many other countries are currently thinking of how they want to handle the growing presence of these contaminants in their waterways. AKVO has the potential to provide a compact, environmentally friendly way to help slow this ongoing problem.

The next time you go to throw out an old CD, or any other household item for that matter, ask yourself: What would MacGyver do? Or, better yet: What would Eden Tech do? You might be holding the building blocks for its next innovative design. ◎

Hellenic Cables, Greece

OPTIMIZING SUBSEA CABLE DESIGNS WITH FINITE ELEMENT MODELING

Wind turbines for offshore wind farms are starting to be built farther out into the ocean. This creates a new need for well-designed subsea cables that can reach longer distances, survive in deeper waters, and better connect our world with sustainable power. Hellenic Cables in Greece uses finite element modeling to analyze and validate underground and subsea cable designs.

by **BRIANNE CHRISTOPHER**

The offshore wind (OSW) industry is one of the most rapidly advancing sources of power around the world. It makes sense: Wind is stronger and more consistent over the open ocean than it is on land. Worldwide demand for energy is expected to increase by 20% in 10 years, with a large majority of that demand supplied by sustainable energy sources like wind power.

Offshore wind farms are made up of networks of turbines. These networks include cables (Figure 1) that connect wind farms to the shore and supply electricity to our power grid infrastructure (Figure 2). Many OSW farms are made up of grounded structures, like monopiles and other types of bottom-fixed wind turbines. The foundations for these structures are expensive to construct and difficult to install in deep sea environments, as the cables have to be buried in the seafloor. Installation and maintenance is easier to accomplish in shallow waters.

The future of offshore wind lies in wind farms that float on ballasts and moorings, with the cables laid directly on the seafloor. Floating wind farms are a great solution when wind farms situated just off the coast grow crowded. They can also take advantage of the bigger and more powerful winds that occur farther out to sea.

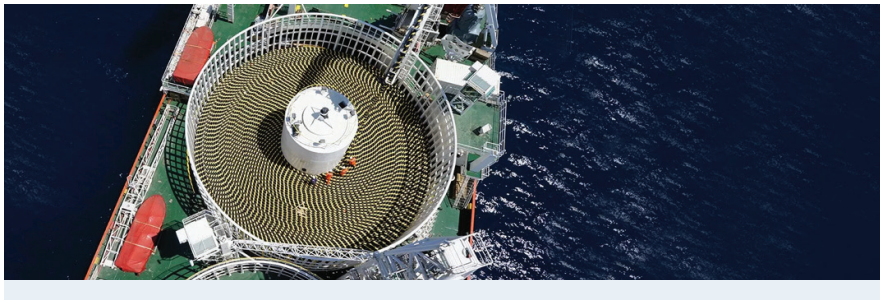


FIGURE 1 A ship hauling coiled cables for subsea installation.

» DESIGN FACTORS FOR RESILIENT SUBSEA CABLES

As the offshore wind industry continues to grow, our need to develop power cables that can safely and efficiently connect these farms to our power grid grows as well.

Before fixing or installing a submarine cable, which can cost billions of dollars, cable designers have to ensure that designs will perform as intended in undersea conditions. This is typically done with the help of computational electromagnetics modeling. To validate cable simulation results, international standards are used, but these standards have not been able to keep up with recent advancements in computational power and simulation software's

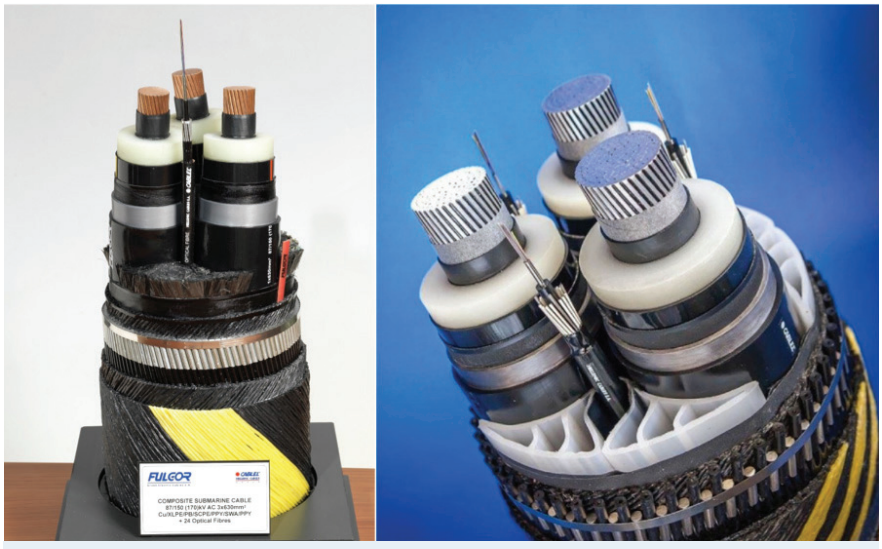


FIGURE 2 Examples of three-core (3C) submarine cables available from Hellenic Cables.

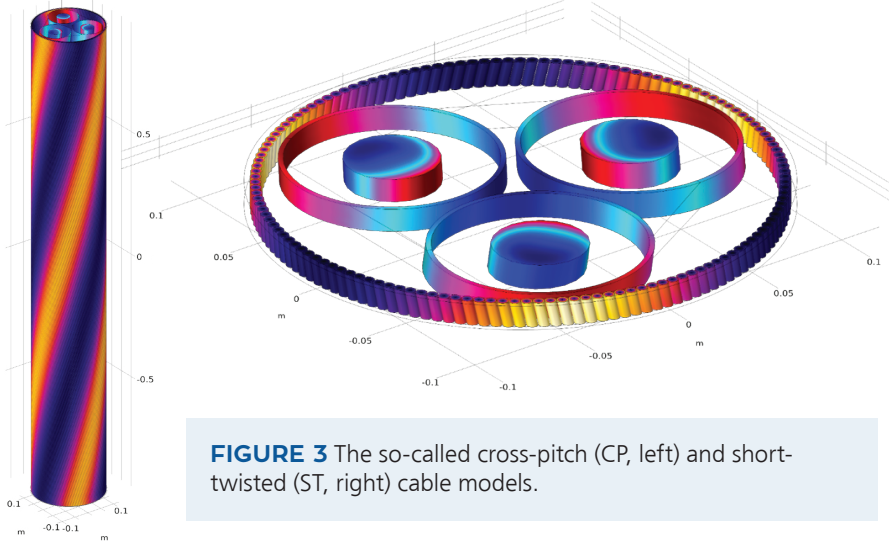


FIGURE 3 The so-called cross-pitch (CP, left) and short-twisted (ST, right) cable models.

growing capabilities. Hellenic Cables, including its subsidiary FULGOR, uses the finite element method (FEM) to analyze its cable designs and compare them to experimental measurements, often getting better results than what the international standards can offer.

» UPDATED METHODOLOGY FOR CALCULATING CABLE LOSSES

The International Electrotechnical Commission (IEC) provides standards for electrical cables, including Standard 60287 1-1 for calculating cable losses and current ratings. One problem with the formulation used in Standard 60287 1-1 is that it overestimates cable losses. Cable designers are forced to adopt a new methodology for performing these analyses, and the team at Hellenic Cables recognizes this. "With a more accurate and realistic model, significant optimization margins are expected," says Dimitrios Chatzipetros, team leader of the Numerical Analysis group at Hellenic Cables. The new methodology will enable engineers to reduce cable cross sections, thereby reducing their costs.

An electric cable is a complex device to model. The geometric structure consists of three main power cores, which are helically twisted with a particular lay length, and hundreds of additional wires — screen or armor wires — that are twisted with a second or third lay length. This makes it difficult to generate the mesh and solve for the electromagnetic fields. "This is a tedious 3D problem with challenging material properties, because some of the elements are ferromagnetic," says Andreas Chrysochos, associate principal engineer in the R&D department of Hellenic Cables.

The Hellenic Cables team first used FEM to model a full cable section of around 30 to 40 meters in length. This turned out to be a huge numerical challenge that could only realistically be solved on a supercomputer. By switching to periodic models with a periodic length equal to the cable's cross pitch, the team reduced the problem from 40 meters down to 2–4 meters. Then they introduced short-twisted periodicity, which reduces the periodic length of the model from meters to centimeters, making it much lighter to solve (Figure 3).

Although the improvements that FEM brings to cable analysis are great, Hellenic Cables still needs to convince its clients that its validated results are more realistic than those provided by the current IEC standard. Clients are often already aware of the fact that IEC 60287 overestimates cable losses, but results visualization and comparison to actual measurements can build confidence in project stakeholders (Figure 4).

» FINITE ELEMENT MODELING OF CABLE SYSTEMS

Electromagnetic interference (EMI) presents several challenges when it comes to designing cable systems — especially the capacitive and inductive couplings between cable conductors and sheaths. For one, when calculating current ratings, engineers need to account for power losses in the cable sheaths during normal operation. In addition, the overvoltages on cable sheaths need to be within acceptable limits to meet typical health and safety standards.

There are three main approaches when it comes to calculating these capacitive and inductive couplings. The first is the complex impedance method (CIM), which calculates the cable system's currents and voltages while neglecting its capacitive currents. Another common method is using

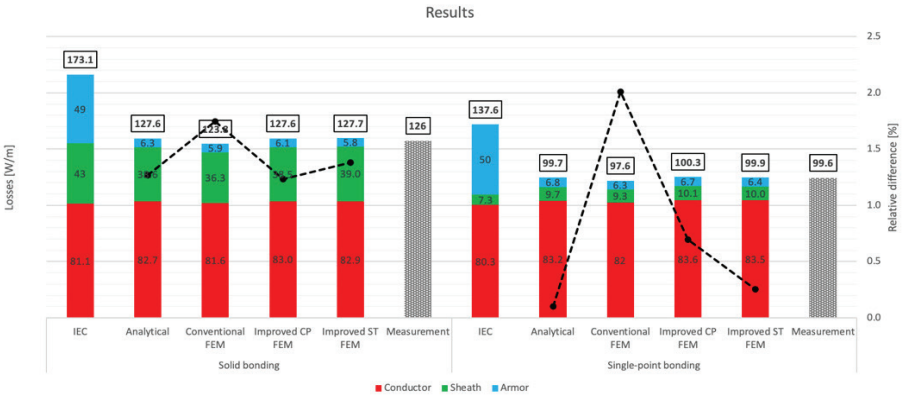


FIGURE 4 The results of two bonding scenarios, solid and single-point bonding, based on a specific cable geometry. The results include losses from IEC 60287 (standard), analytical calculations, conventional FEM, improved CP FEM (based on the cross-pitch model), improved ST FEM (based on the short-twisted model), and measurements.

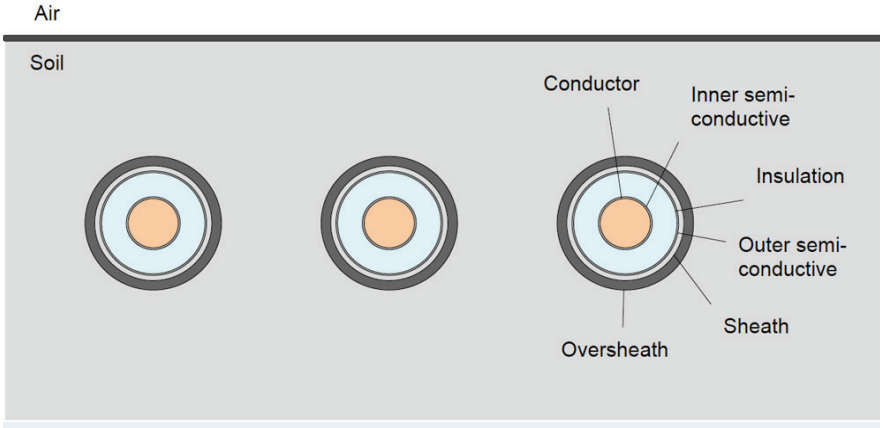


FIGURE 5 Cable model geometry.

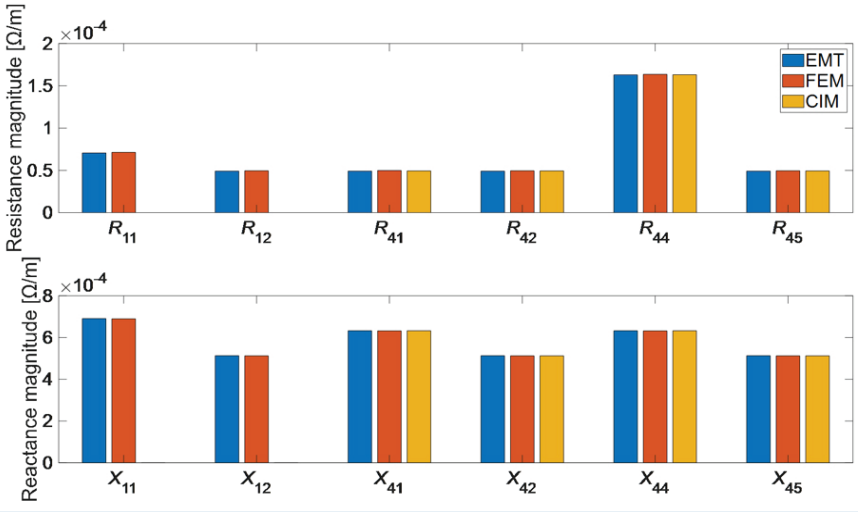


FIGURE 6 Results comparison between EMT, FEM, and CIM.

This story has been abridged. Read the full article at comsol.com/stories.

electromagnetic transients program (EMT) software, which can be used to analyze electromagnetic transients in power systems using both time- and frequency-domain models.

The third method, FEM, is the foundation of the COMSOL Multiphysics® software. The Hellenic Cables team used COMSOL Multiphysics and the add-on AC/DC Module to compute the electric fields, currents, and potential distribution in conducting media. "The AC/DC Module and and the solvers behind it are very robust and efficient for these types of problems," says Chrysochos.

The Hellenic Cables team compared the three methods when analyzing an underground cable system with an 87/150 kV nominal voltage and 1000 mm^2 cross section (Figure 5). The team modeled the magnetic field and induced-current-density distributions in and around the cable system's conductors, accounting for the bonding type with an external electrical circuit. The results between all three methods show good agreement for the cable system for three different configurations: solid bonding, single-point bonding, and cross bonding (Figure 6). This agreement demonstrates that FEM can be applied to all types of cable configurations and installations when taking into account capacitive and inductive coupling.

» A BRIGHT AND WINDY FUTURE

The Hellenic Cables team plans to continue the important work of further improving all of the cable models they have developed. The team has also performed research into high-voltage direct current (HVDC) cables, which involve cross-linked polyethylene (XLPE) insulation and voltage source converter (VSC) technology. HVDC cables can be more cost efficient for systems installed over long distances.

Like the wind used to power offshore wind farms, electrical cable systems are all around us. Even though we cannot always see them, they are working hard to ensure we have access to a high-powered and well-connected world. Optimizing the designs of subsea cables is an important part of building a sustainable future.

Alfred Wegener Institute, Germany

FORECASTING THE ICE LOSS OF GREENLAND'S GLACIERS WITH VISCOELASTIC MODELING

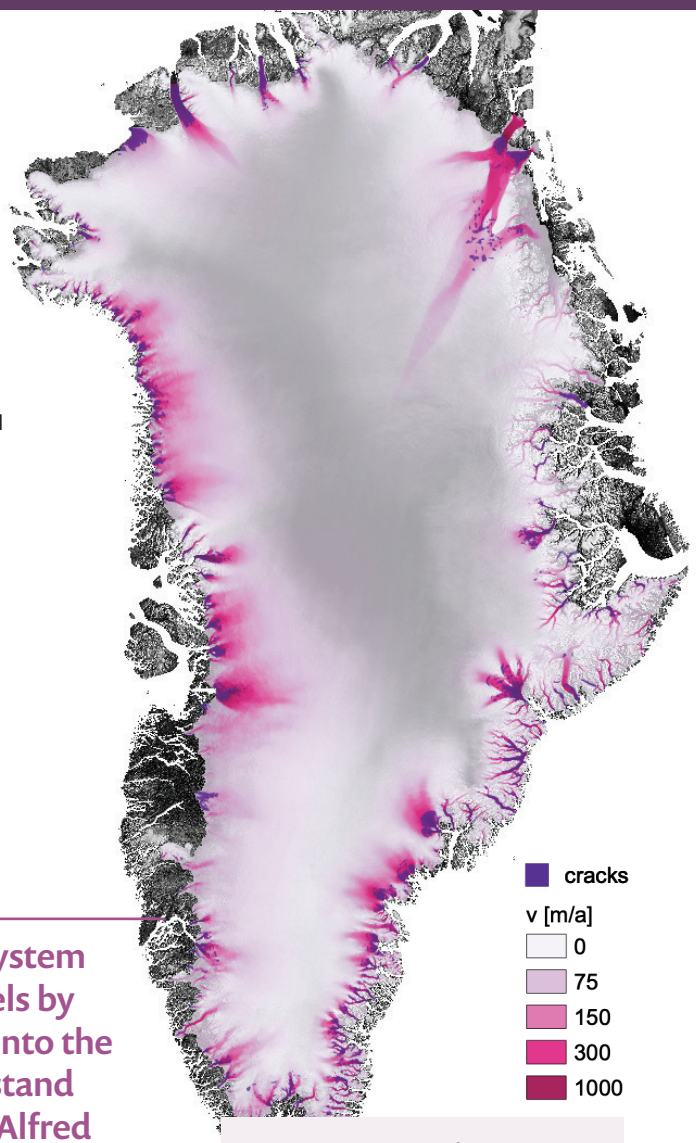


FIGURE 1 A map of Greenland. The color scale indicates the velocity of glacial movement in certain areas. Note that areas of greatest movement tend to be near the coast. Solid purple zones indicate the locations of massive cracks in the ice cover.

The Northeast Greenland Ice Stream glacial system contains enough water to raise global sea levels by more than a meter — and its discharge of ice into the ocean has been accelerating. To better understand and predict this discharge, researchers at the Alfred Wegener Institute have developed an improved viscoelastic model to capture how tides and subglacial topography are contributing to glacial flow.

by **ALAN PETRILLO**

To someone standing near a glacier, it may seem as stable and permanent as anything on Earth can be. However, Earth's great ice sheets are always moving and evolving. In recent decades, this ceaseless motion has accelerated. In fact, ice in polar regions is proving to be not just mobile, but alarmingly mortal.

Rising air and sea temperatures are speeding up the discharge of glacial ice into the ocean, which contributes to global sea level rise. This ominous progression is happening even faster than anticipated. Existing models of glacier dynamics and ice discharge underestimate the actual rate of ice loss in recent decades. This makes the work of Angelika Humbert, a physicist studying Greenland's Nioghalvfjerdsbræ outlet glacier, especially important — and urgent.

As the leader of the Modeling Group in the Section of Glaciology at the Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research in Bremerhaven, Germany, Humbert works to extract broader lessons from Nioghalvfjerdsbræ's ongoing decline. Her research combines data from field observations with viscoelastic modeling of ice sheet behavior. Through improved modeling of elastic effects on glacial flow, Humbert and her team seek to better predict ice loss and the resulting impact on global sea levels.

She is acutely aware that time is short. "Nioghalvfjerdsbræ is one of the last three 'floating tongue' glaciers in Greenland," explains Humbert. "Almost all of the other floating tongue formations have already disintegrated."

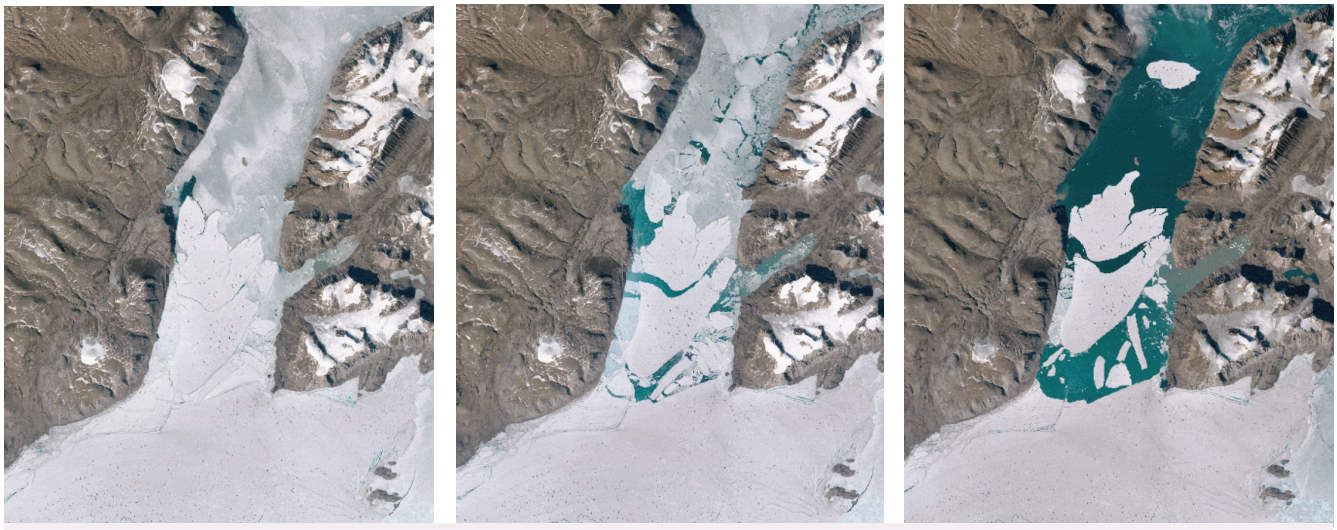


FIGURE 2 A floating portion of the Nioghalvfjerdsbræ outlet glacier fractures and breaks away in this sequence of images from June and July of 2020.

» ONE GLACIER THAT HOLDS 1.1 METERS OF POTENTIAL GLOBAL SEA LEVEL RISE

The North Atlantic island of Greenland is covered with the world's second largest ice pack after that of Antarctica (Figure 1). Greenland's sparsely populated landscape may seem unspoiled, but climate change is actually tearing away at its icy mantle.

The ongoing discharge of ice into the ocean is a "fundamental process in the ice sheet mass-balance," according to a 2021 article in *Communications Earth & Environment* by Humbert and her colleagues. The article notes that the entire Northeast Greenland Ice Stream contains enough ice to raise global sea levels by 1.1 meters. While the entire formation is not expected to vanish, Greenland's overall ice cover has declined dramatically since 1990. This process of decay has not been linear or uniform across the island. Nioghalvfjerdsbræ, for example, is now Greenland's largest outlet glacier. The nearby Petermann Glacier used to be larger, but has been shrinking even more quickly.

» EXISTING MODELS UNDERESTIMATE THE RATE OF ICE LOSS

Greenland's overall loss of ice mass is distinct from "calving", which is the breaking off of icebergs from glaciers' floating tongues. While calving does not directly raise sea levels, the calving process can quicken the movement of land-based ice toward the coast. Satellite imagery from the European Space Agency (Figure 2) has captured a rapid and dramatic calving event in action. Between June 29 and July 24 of 2020, a 125 km^2 floating portion of Nioghalvfjerdsbræ calved into many separate icebergs, which then drifted off to melt into the North Atlantic.

Direct observations of ice sheet behavior are valuable, but insufficient for predicting the trajectory of Greenland's ice loss. Glaciologists have been building and refining ice sheet models for decades, yet, as Humbert says, "There is still a lot of uncertainty around this approach." Starting in 2014, the team at AWI joined 14 other research groups to compare and refine their forecasts of potential ice loss through 2100. The project also compared projections for past years to ice losses that actually occurred. Ominously, the experts' predictions were "far below the actually observed losses" since 2015, as stated by Martin Rückamp of AWI. He says, "The models for Greenland underestimate the current changes in the ice sheet due to climate change."

» VISCOELASTIC MODELING TO CAPTURE FAST-ACTING FORCES

Angelika Humbert has personally made numerous trips to Greenland and Antarctica to gather data and research samples, but she recognizes the limitations of the direct approach to glaciology. "Field operations are very costly and time consuming, and there is only so much we can see," she says. "What we want to learn is hidden inside a system, and much of that system is buried beneath many tons of ice! We need modeling to tell us what behaviors are driving ice loss, and also to show us where to look for those behaviors."

Since the 1980s, researchers have relied on numerical models to describe and predict how ice sheets evolve. "They found that you could capture the effects of temperature changes with models built around a viscous power law function," Humbert explains. "If you are modeling stable, long-term behavior, and you get your viscous deformation and sliding right, your model can do a decent job. But if you are trying to capture loads that are changing on a short time scale, then you need a different approach."

What drives short-term changes in the loads that affect ice sheet behavior? Humbert and the AWI team focus on two sources of these significant but poorly understood forces: oceanic tidal movement under floating ice tongues (such as the one shown in Figure 2) and the ruggedly uneven landscape of Greenland itself. Both tidal movement and Greenland's topography help determine how rapidly the island's ice cover is moving toward the ocean.

To investigate the elastic deformation caused by these factors, Humbert and

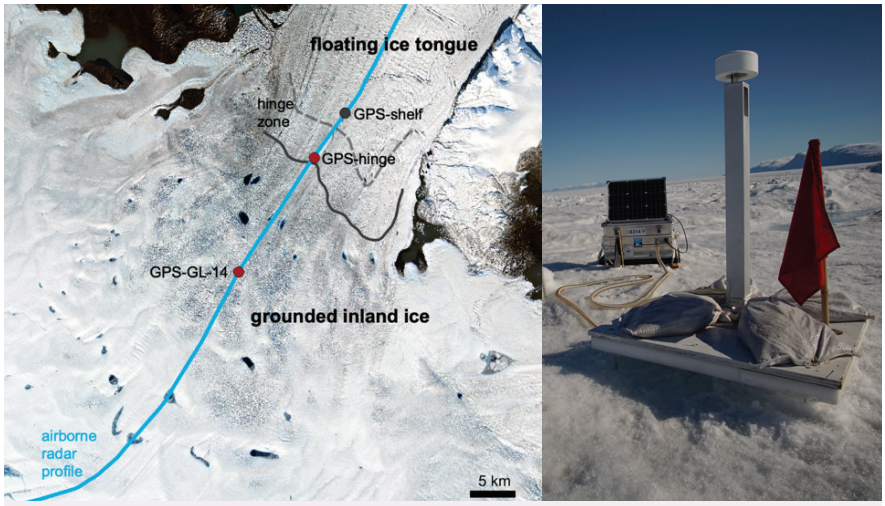


FIGURE 3 Positions of GPS measuring stations mounted on Nioghalvfjerdsbræ (left) and an individual station (right). Photo at right by Ole Zeising of AWI.

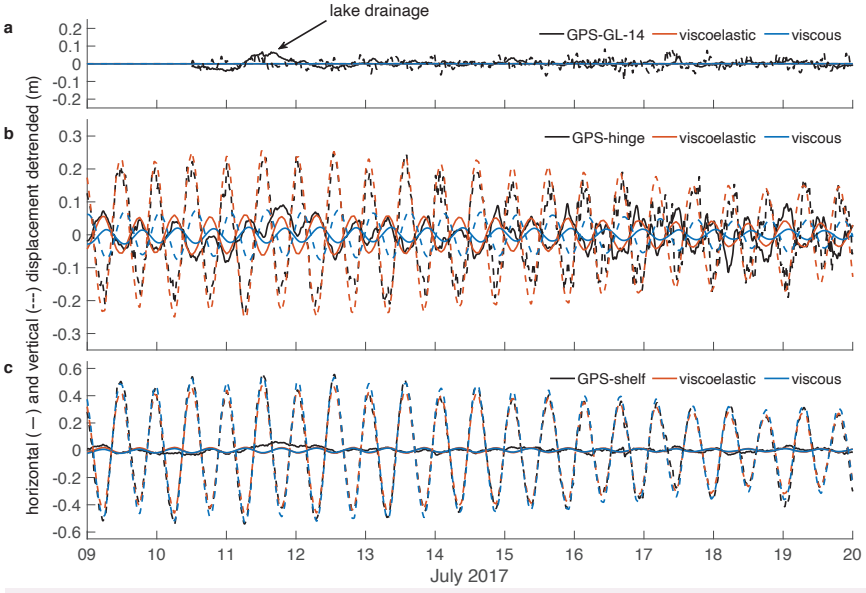


FIGURE 4 Displacement over time of glacier ice at three locations on Nioghalvfjerdsbræ. Black lines show measured displacement, orange lines show simulated displacement according to the "COMice-ve" viscoelastic model that AWI built in the COMSOL® software, and blue lines show simulated displacement in a viscous model.

her team built a viscoelastic model of Nioghalvfjerdsbræ in the COMSOL Multiphysics® software. The glacier model's geometry was based on data from radar surveys. The model solved underlying equations for a viscoelastic Maxwell material across a 2D model domain consisting of a vertical cross section along the blue line shown in Figure 3. The simulated results were then compared to actual field measurements of glacier flow obtained by four GPS stations.

» HOW CYCLING TIDES AFFECT GLACIER MOVEMENT

The tides around Greenland typically raise and lower the coastal water line between 1 and 4 meters per cycle. This action exerts tremendous force on outlet glaciers' floating tongues, and these forces are transmitted into the land-based parts of the glacier as well. AWI's viscoelastic model explores how these cyclical changes in stress distribution can affect the glacier's flow toward the sea.

The charts in Figure 4 present the measured tide-induced stresses acting on Nioghalvfjerdsbræ at three locations, superimposed on stresses predicted by viscous and viscoelastic simulations. Chart *a* shows how displacements decline further when they are 14 kilometers inland from the grounding line (GL). Chart *b* shows that cyclical tidal stresses lessen at GPS-hinge, located in a bending zone near the grounding line between land and sea. Chart *c* shows activity at the location called *GPS-shelf*, which is mounted on ice floating in the ocean. Accordingly, it shows the most pronounced waveform of cyclical tidal stresses acting on the ice.

"The floating tongue is moving up and down, which produces elastic responses in the land-based portion of the glacier," says Julia Christmann, a mathematician on the AWI team who plays a key role in constructing its simulation models. "There is also a subglacial hydrological system of liquid water between the inland ice and the ground. This basal water system is poorly known, though we can see evidence of its effects." For example, chart *a* shows a spike in stresses below a lake sitting atop the glacier. "Lake water flows down through the ice, where it adds to the subglacial water layer and compounds its lubricating effect," Christmann says.

The plotted trend lines highlight the greater accuracy of the team's new viscoelastic simulations, as compared to purely viscous models. As Christmann explains, "The viscous model does not capture the full extent of changes in stress, and it does not show the correct amplitude. (See chart *c* in Figure 4). In the bending zone, we can see a phase shift in these forces due to elastic response." Christmann continues, "You can only get an accurate model if you account for viscoelastic 'spring' action."

» MODELING ELASTIC STRAINS FROM UNEVEN LANDSCAPES

The crevasses in Greenland's glaciers reveal the unevenness of the underlying landscape (Figure 5). Crevasses also provide further evidence that glacial ice is not a purely viscous material. "You can watch a glacier over time and see that it creeps, as a viscous material would,"

FIGURE 5 Aerial view of Nioghalvfjerdsbræ showing the extensive patterns of the crevasses. Photo by Julia Christmann of AWI.

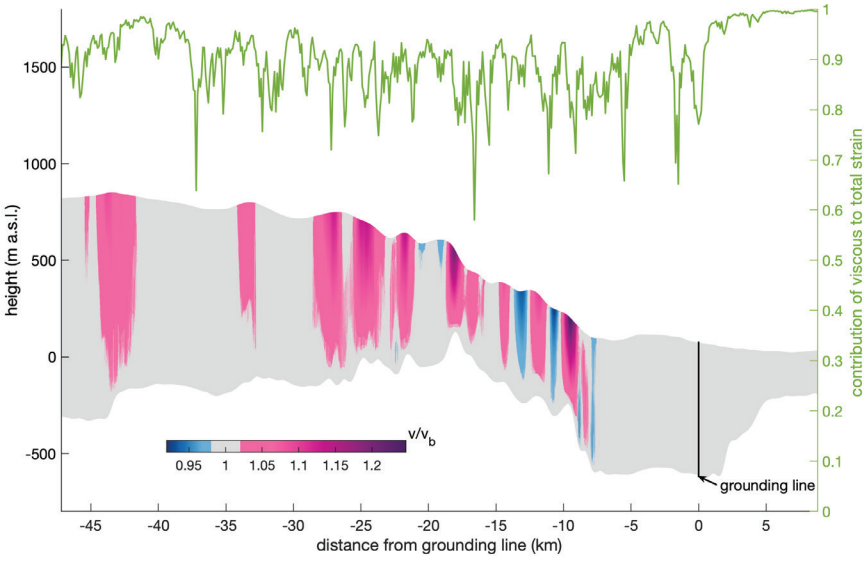


FIGURE 6 A cross section of Nioghalvfjerdsbræ (left scale) showing vertical velocities of ice movement inside the glacier, as compared to movement at the base of the glacier. Blue areas are moving more slowly than basal velocity, while pink and purple areas are moving more quickly than ice at the base. The green line (right scale) shows the proportion of viscous strain to total strain along the cross-section line.

says Humbert. However, a purely viscous material would not form persistent cracks the way that ice sheets do. "From the beginning of glaciology, we have had to accept the reality of these crevasses," she says. The team's viscoelastic model provides a novel way to explore how the land beneath Nioghalvfjerdsbræ facilitates the emergence of crevasses and affects glacial sliding.

"When we did our simulations, we were surprised at the amount of elastic strain created by topography," Christmann explains. "We saw these effects far inland, where they would have nothing to do with tidal changes."

Figure 6 shows how vertical deformation in the glacier corresponds to the underlying landscape and helps researchers understand how localized elastic vertical motion affects the entire sheet's horizontal movement. Shaded areas indicate velocity in that part of the glacier compared to its basal velocity. Blue zones are moving vertically at a slower rate than the sections that are directly above the ground, indicating that the ice is being compressed. Pink and purple zones are moving faster than ice at the base, showing that ice is being vertically stretched.

These simulation results suggest that the AWI team's improved model could provide more accurate forecasts of glacial movements. "This was a 'wow' effect for us," says Humbert. "Just as the up and down of the tides creates elastic strain that affects glacier flow, now we can capture the elastic part of the up and down over bedrock as well."

» SCALING UP AS THE CLOCK RUNS DOWN

The improved viscoelastic model of Nioghalvfjerdsbræ is only the latest example of Humbert's decades-long use of numerical simulation tools for glaciological research. "COMSOL® is very well suited to our work," she says. "It is a fantastic tool for trying out new ideas. The software makes it relatively easy to adjust settings and conduct new simulation experiments without having to write custom code." Humbert's university students frequently incorporate simulation into their research. Examples include Julia Christmann's PhD work on the calving of ice shelves, and another degree project that modeled the evolution of the subglacial channels that carry meltwater from the surface to the ice base.

The AWI team is proud of its investigative work, but Humbert is fully cognizant of just how much information about the world's ice cover remains unknown — and that time is short. "We cannot afford Maxwell material simulations of all of Greenland," Humbert concedes. "We could burn years of computational time and still not cover everything. But perhaps we can parameterize the localized elastic response effects of our model, and then implement it at a larger scale," she says.

This scale defines the challenges faced by 21st-century glaciologists. The size of their research subjects is staggering, and so is the global significance of their work. Even as their knowledge is growing, it is imperative that they find more information, more quickly. Angelika Humbert would welcome input from people in other fields who study viscoelastic materials. "If other COMSOL users are dealing with fractures in Maxwell materials, they probably face some of the same difficulties that we have, even if their models have nothing to do with ice!" she says. "Maybe we can have an exchange and tackle these issues together."

Perhaps, in this spirit, we who benefit from the work of glaciologists can help shoulder some of the vast and weighty challenges they bear. ◎

Virtual Product Development with Acoustic Simulation

by **ROGER SHIVELY**

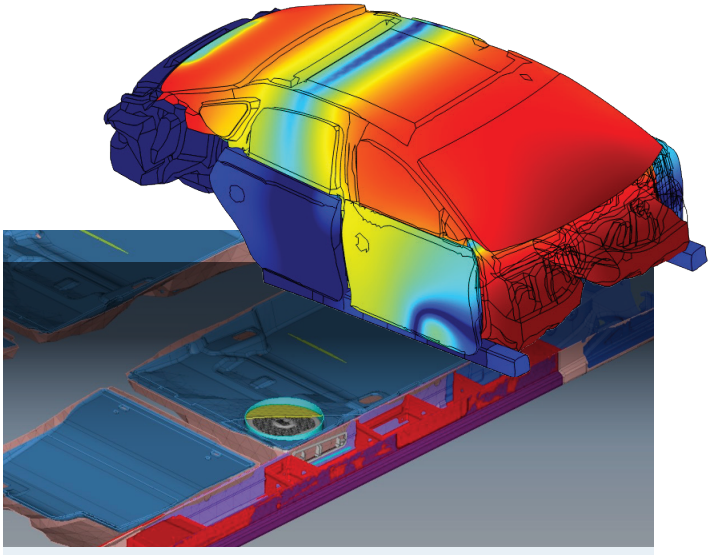
Among original equipment manufacturers (OEMs) worldwide, particularly within the automotive market, the use of simulation software has helped control costs by reducing the need for physical prototypes.

Simulation was first used in the automotive sector for vehicle crash safety, durability, and noise, vibration, and harshness (NVH) research. These simulations have helped pave the way for efficient audio system and vehicle acoustics model building. For example, meshes created for crash, durability, and noise models are being repurposed for acoustic meshes. Whether this is done internally by OEMs and component manufacturers or by independent consulting companies like JJR Acoustics, repurposing these meshes saves the resources required to create them from raw CAD files.

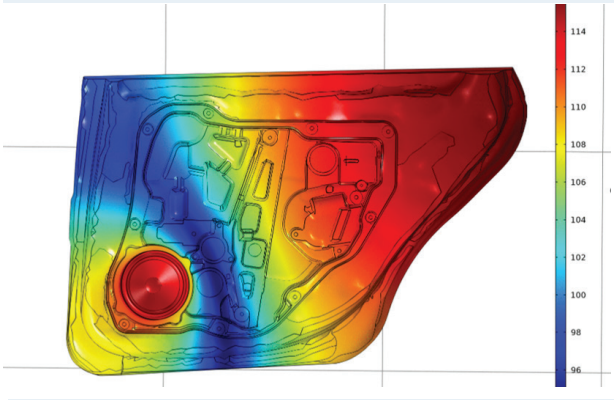
Acoustic simulation powered by COMSOL Multiphysics® helps automotive audio engineers integrate an audio system's loudspeakers into the vehicle while maintaining the integrity of the loudspeakers' design quality. Much of the simulation, tuning, and auralization that's required is being done outside the lab space now. Exploring tuning options — whether virtually or in the lab —helps acoustics engineers develop an understanding of the acoustic space and loudspeaker system to find a path to the optimal in-vehicle audio experience. By then changing the trim, speaker, and speaker location and finding another path, knowledge is built. With multiphysics simulation software, the insights of this optimization and iteration process are now available virtually. Models developed into digital twins or based on existing digital twins are enabling virtual acoustical tuning of concept cars while they are still in the design phase. While this digital workflow is familiar to engineers using traditional physical prototyping and mechanical simulation, it also enables fast and cost-efficient exploration of the entire design space before committing to the interior architecture.

Applications of system-level automotive simulations enabled by COMSOL Multiphysics include optimizing loudspeaker placement and reducing negative structural interactions of loudspeakers and mounting locations. This type of simulation requires the computation of results for a great range of frequencies throughout the car cabin. The acoustic frequency response averaged over the location of a listener's head location is a key factor in determining audio quality. This can be done for multiple listening positions in the vehicle.

Going forward, the design of active noise control along with music playback will be a major focus for audio and acoustics engineers. Multiphysics simulation of the acoustic transfer paths for noise and its cancellation will be crucial for understanding the effects of these phenomena and applying this insight to the design process. ◎



An example of optimizing the location of the subwoofer mounting, the sound pressure level (SPL) mode, and SPL response at the listener.



Structural interaction of woofer and door.

ABOUT THE AUTHOR

Roger Shively is a cofounder and principal of JJR Acoustics (Seattle, WA). He has more than 34 years of experience in engineering research and development, with significant experience in product realization and in launching new products at OEM manufacturers around the world. Before cofounding JJR Acoustics in 2011, Roger worked as chief engineer of acoustic systems as well as functional manager for North American and Asian engineering product development teams in the Automotive Division of Harman International Industries Inc., a journey that began in 1986.

TOP TECH 2023

GREEN HYDROGEN

AIRSHIPS

OPTICAL INTERCONNECTS

FLYING CARS

AUTONOMOUS EVS

BREEDER REACTORS

LASER WEAPONS

CRYPTOCURRENCY

QUANTUM CHIPS

ELECTROCEUTICALS

SUPERCOMPUTERS

SATELLITE PHONES

and more...

EACH JANUARY, the editors of *IEEE Spectrum* offer up some predictions about technical developments we expect to be in the news over the coming year. You'll find a couple dozen of those described in the following special report. Of course, the number of things we could have written about is far higher, so we had to be selective in picking which projects to feature. And we're not ashamed to admit, gee-whiz appeal often shaped our choices. • For example, this year's survey includes an odd pair of new aircraft that will be taking to the skies. One, whose design was inspired by the giant airships of years past, is longer than a football field; the other, a futuristic single-seat vertical-takeoff craft powered by electricity, is about the length of a small car. • While some of the other stories might not light up your imagination as much, they highlight important technical issues the world faces—like the challenges of shifting from fossil fuels to a hydrogen-based energy economy or the threat that new plutonium breeder reactors in China might accelerate the proliferation of nuclear weapons. So whether you prefer reading about topics that are heavy or light (even lighter than air), you should find something here to get you warmed up for 2023. ▶

Making Green Hydrogen a Reality Down Under

Proposals to make hydrogen from renewable electricity in Australia exceed the country's generating capacity

BY PETER FAIRLEY

For several months now, 20 teams of Australian high-school students have been designing fuel-cell cars to compete in the country's inaugural Hydrogen Grand Prix. They've been studying up on renewable energy, hydrogen power, and electric vehicles, preparing for the big day in April when their remote-controlled vehicles will rumble for 4 hours in Gladstone, a port city in Queensland. The task: make the most of a 30-watt fuel cell and 14 grams of hydrogen gas.

A few months later and some 800 kilometers up Queensland's coast, Grand Prix corporate cosponsor Ark Energy aims to apply the same basic hydrogen and fuel-cell components—albeit scaled up more than 3,500 times. By 2023's third quarter, Ark expects five of the world's largest fuel-cell trucks to be hauling concentrated zinc ore and finished ingots between a zinc refinery and the nearby port of Townsville. The carbon-free rigs will pack 50 kilos of hydrogen zapped from water using electricity from the refinery's dedicated solar power plant.

Welcome to Australia, where a green-hydrogen boom is in full swing. Both the massive and the toy-size vehicles are about selling Australians on the transformative potential of green hydrogen—hydrogen gas produced from renewable energy—to decarbonize their fossil-fuel-based economy. And while coal plants still supplied over half of Australia's power in 2021, change is afoot. The government elected last year passed the country's first climate-action law in more than a decade. And green hydrogen is the centerpiece of its clean-economy growth plan.

Resource-poor Asian neighbors such as Japan and Korea are also counting on Aussie green hydrogen to help get them off fossil fuels in the decades ahead.

Add up the capacity figures in all of Australia's current proposals to produce green hydrogen and the sum exceeds Australia's power-generating capacity. It's all part of a green-hydrogen wave that's spreading worldwide.

Observers caution that some of these green-hydrogen projects will never produce a thimbleful of hydrogen—an echo

Illustration by MCKIBILLO

of the hydrogen boom a generation ago that ultimately went bust. "It's very easy in this current phase for two people you've never heard about to create a 30-gigawatt project and put out a press release," says David Norman, CEO for the clean-energy research organization Future Fuels Cooperative Research Centre, in Wollongong, New South Wales.

Phantom projects are not a problem confined to Australia. Only 10 percent of the US $240 billion worth of hydrogen projects announced worldwide are actually moving forward, according to a September 2022 study by consultancy McKinsey & Company. Yet many more are actually needed. Building every electrolyzer promised for 2030 would provide only about one-sixth of the green hydrogen required to meet climate targets, according to figures from the International Energy Agency in Paris.

Amid this noisy background, Queensland is home to the two projects most likely to boost the credibility of Australia's green-hydrogen juggernaut in 2023. Ark Energy's project is part of a clean-energy blitz in Australia by its parent company, Seoul-based metal-refining giant Korea Zinc. The other glimmer of reality is a project in Gladstone to build one of the world's largest electrolyzer-manufacturing plants, which promises to provide a local source of equipment amid ongoing chaos in global supply chains.

The 124-megawatt solar plant adjacent to Korea Zinc's Townsville refinery, completed in 2018, cut a quarter of the coal-heavy grid power it had been using to run its power-intensive electrolytic process. The coming fuel-cell trucks will trim its diesel consumption.

Ark Energy CEO Daniel Kim says Korea Zinc launched his firm in 2021 to help shift its Australian operations to 80 percent renewable energy by 2030 and, in the process, pave a path for 100 percent renewable energy group-wide by 2050. Kim says the 2050 goal requires green hydrogen—or a more exportable fuel made from it—because Korea Zinc does most of its refining in South Korea, where there's limited space for solar and wind plants.

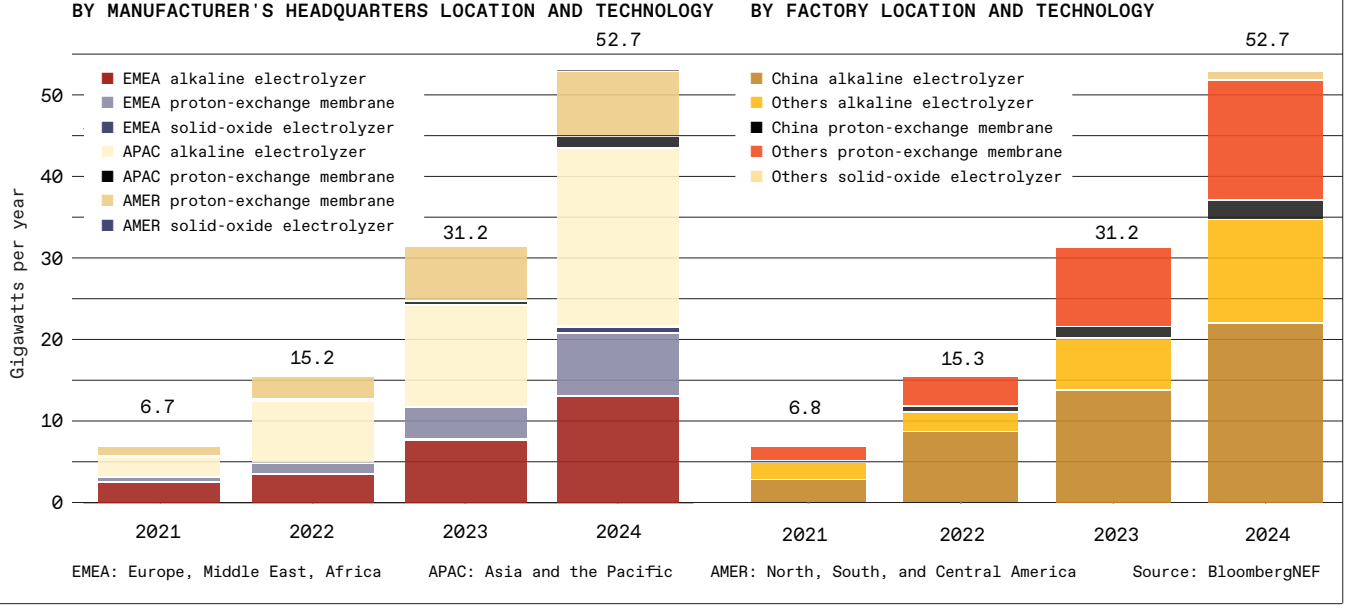
150 GW

Amount of wind and solar Fortescue will have to add to fulfill its green-hydrogen ambitions—more than the total installed generating capacity of France

Ark's first move was to access more renewable power in Australia by buying into a 923-MW wind farm that's expected to spin up in 2024. Next it ordered equipment for the Townsville truck project to begin exploring green hydrogen's capabilities and challenges. "To become a low-cost producer of green hydrogen, we first have to become an extreme user—to make it pervasive across our business. Diesel replacement for heavy trucks was the best prospective use," Kim says.

Today, 28 heavy-duty diesel-powered trucks operate at the Townsville refinery. When ships arrive at port with zinc concentrate, or tie up to take on zinc ingots, the rigs haul triple-trailers and loop the

ESTIMATED ANNUAL ELECTROLYZER MANUFACTURING CAPACITY, 2021-2024 BloombergNEF predicts that the annual manufacturing capacity worldwide for hydrogen-producing electrolyzers will more than triple in the next two years. Much of this growth will be accomplished by companies headquartered in China, Australia, and Europe [below, left]—and a large share of it will be alkaline-type electrolyzers manufactured in China [right].



The Sun Metals solar farm, completed in 2018, supplies electricity to a zinc refinery in Townsville, Qld., Australia. The AUS $200 million, 120-hectare plant can supply 124 megawatts under ideal conditions. The plant is now owned by Ark Energy, a subsidiary of Korea Zinc, which also owns the adjacent refinery. By the end of 2023, Ark Energy plans to commission a fleet of fuel-cell trucks powered by green hydrogen to haul zinc concentrates and ingots between the refinery and a nearby port.

30 km from port to plant and back nonstop for as many as eight days. Time is money, says Kim, because occupying a berth in port can cost a whopping AUS $22,000 (US $13,800) a day. Even if a battery-powered truck could handle the refinery's 140,000-tonne loads, Kim says his company couldn't afford to wait for batteries to recharge.

In 2021, Ark Energy took a stake in Hyzon Motors, one of the few firms working on ultraheavy trucks powered by fuel cells. Hyzon, based in Rochester, N.Y., agreed to equip some of its first extra-beefy fuel-cell rigs with the right-hand drive and wider carriage required in Australia—something other developers couldn't offer until 2025 or 2026. "We're bringing forward the transition of Australia's ultraheavy transport sector by several years," says Kim.

To fuel the trucks, Ark Energy ordered a 1-MW electrolyzer from Plug Power, based in Latham, N.Y. Kim anticipated that construction of the electrolyzer facility would start around the end of 2022, and vowed that five fuel-cell trucks would be looping to port and back on hydrogen gas in the third quarter of 2023 or sooner.

Kim says these vehicles will cost "a little over three times" that of an equivalent diesel-fueled hauler, up front, but the overall project should break even or even save money over the trucks' projected 10-year operating life. Government grants and loans and high diesel prices help make hydrogen competitive. The trucks' unchanging route was also a plus: The relatively flat loop enabled use of a smaller, cheaper, fuel cell. "This is a dedicated truck for a dedicated purpose," Kim notes.

Ark Energy expects to start exporting renewable energy around 2030. In contrast, the team delivering Queensland's second dose of green hydrogen realism this year could begin commercial-scale exports in 2025. The AUS $114 million (US $72 million) electrolyzer plant rising in Gladstone is the first brick-and-mortar green-hydrogen move by mining magnate Andrew Forrest, Australia's boldest, and wealthiest, green-hydrogen proponent.

10%

Percentage of the US $240 billion worth of hydrogen projects announced worldwide that are actually moving forward, according to a September 2022 study

Forrest became the second-richest man in Australia running Perth-based Fortescue Metals Group, which disrupted the global iron-ore business through vertical integration and aggressive cost cutting.

Now Fortescue is applying the same strategy to green hydrogen. Forrest vows to invest US $6.2 billion to produce 15 million tonnes of green hydrogen per year by 2030—50 percent more than what the European Union says it needs to import to get off Russian energy and to cut carbon emissions. Doing so will require about 150 GW of wind and solar generation—more than the total installed generating capacity of France. The move is projected to eliminate 3 million tonnes of carbon per year—slashing Fortescue's emissions to zero and saving it US $818 million per year.

Cameron Smith, head of manufacturing for Fortescue's green-energy subsidiary, Fortescue Future Industries, says getting there means cutting costs until

Fortescue's growth plan anticipates shipping most of its green hydrogen out of Australia to clean up heavy vehicles, industries, and power grids worldwide.

ARK ENERGY

"It's very easy in this current phase for two people you've never heard about to create a 30-gigawatt project and put out a press release," says one observer.

the company's renewable energy is cheaper than fossil fuels. "Our objective here is to make fossil fuels irrelevant," Smith declares.

Fortescue is building its own electrolyzer production plant in spite of a global glut. Market analysts at BloombergNEF project that manufacturing capacity for electrolyzers will exceed demand 10- to 15-fold this year. Smith says that's not a major concern for Fortescue, given the company's imperative to cut costs and to quickly bring green-hydrogen production on line. "We don't need to make everything, but we need a credible pathway to do so if we can't get the equipment we need at the cost and quality we need to make all our projects viable," he says.

The Gladstone plant's 13,000-square-meter envelope is already in place, and Smith anticipates installation of one line's robotic machines during the second quarter of 2023. He expects the plant will end the year as a "gigawatt-scale" electrolyzer factory: producing enough electrolyzers in a year to consume 1 GW of electricity. And he expects production capacity to double with a second line early in 2024.

Fortescue expects green hydrogen to help its own operations reach net-zero carbon emissions by 2040. But its growth plan, like Ark Energy's, anticipates exporting most of its green hydrogen to clean up heavy vehicles, industries, and power grids worldwide. First, though, they will have to make it shippable.

Shipping hydrogen is pricey. As either a gas or a liquid, it has relatively low volumetric energy density. So most of Australia's prospective green-hydrogen mega-producers expect to move their energy overseas by converting green hydrogen to ammonia—a chemical precursor for nitrogen fertilizers that already ships worldwide. Ammonia is primarily produced from hydrogen, although today it's typically done using hydrogen made with natural gas rather than electrolysis.

Exported ammonia made in Australia from green hydrogen could already outcompete ammonia produced in Europe with natural gas, according to calculations by BloombergNEF, and proposed projects are multiplying. Ark Energy recently formed an industrial consortium to use 3 GW of renewable power to produce "green ammonia" for export to Korea, although first shipments wouldn't happen until after 2030.

Fortescue has even bigger long-term plans, and is already sizing up a way to jump-start ammonia exports. It is considering refitting a 54-year-old fertilizer plant in Brisbane, which was slated to shut down early this year due to skyrocketing natural-gas prices. Fortescue and the plant's owner are considering installing 500 MW of electrolyzers so they can restart the plant on green hydrogen around 2025.

Amid all of these grand plans, what remains to be seen, says hydrogen analyst Martin Tengler at BloombergNEF's Tokyo office, is whether green-ammonia exports can truly meet people's energy needs.

Ammonia doesn't burn well on its own, he notes, and converting exported ammonia back to hydrogen for steel plants or fuel-cell vehicles requires a lot of energy. "You're using energy to import energy. If you need green hydrogen in Europe, it's probably cheaper to make green hydrogen in Europe," Tengler concludes.

Some plans for green ammonia could actually extend fossil-fuel consumption and thus delay climate action. For example, some Japanese and Korean power producers have announced plans to burn green ammonia in coal-fired power plants to reduce emissions.

In September, BloombergNEF estimated that power from Japanese coal plants burning 50 percent green ammonia from Australia would cost US $136 per megawatt-hour in 2030—more than it projects for power from offshore wind and solar plants in Japan backed up with battery storage. "It's not the most economical way to use ammonia," Tengler says, "or the cheapest way for Japan and Korea to decarbonize."

In other words, even if green hydrogen gets real this year, there's much to learn about what it should be used for, and where. ■

MODULAR NUCLEAR POWER IS NUCLEATING

Korean manufacturer Doosan is set to start producing components of what could be the world's first modular nuclear power plant, in late 2023. The components are for startup NuScale, whose design promises to drastically reduce cost and installation time. Unlike today's power plants, which are constructed completely on-site, these reactors can be mass-produced in a factory and shipped to power stations worldwide. Each houses between 4 and 12 self-contained reactor modules depending on local needs. The first power plant using NuScale's technology is set to start generating electricity in 2029 at the Idaho National Laboratory, as part of the Carbon Free Power Project.

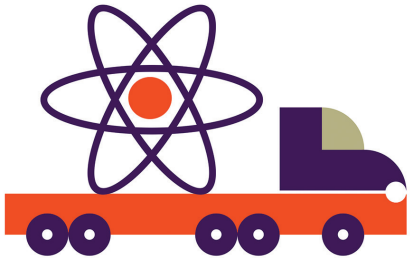


Illustration by Greg Mably

The Return of the Airship

LTA Research's Pathfinder 1 will begin test flights in 2023

By MICHAEL KOZIOL

At Moffett Field in Mountain View, Calif., Lighter Than Air (LTA) Research is floating a new approach to a technology that saw its rise and fall a century ago: airships. Although airships have long since been supplanted by planes, LTA, which was founded in 2015 by CEO Alan Weston, believes that through a combination of new materials, better construction techniques, and technological advancements, airships are poised to—not reclaim the skies, certainly—but find a new niche.

Although airships never died off entirely—the Goodyear blimps, familiar to sports fans, are proof of that—the industry was already in decline by 1937, the year of the *Hindenburg* disaster. By the end of World War II, airships couldn't compete with the speed airplanes offered, and they required larger crews. Today, what airships still linger serve primarily for advertising and sightseeing.

LTA's *Pathfinder 1* carries bigger dreams than hovering over a sports stadium, however. The company sees a natural fit for airships in humanitarian and relief missions. Airships can stay aloft for long periods of time, in case ground conditions aren't ideal, have a long range, and carry significant payloads, according to Carl Taussig, LTA's chief technical officer.

Pathfinder 1's cigar-shaped envelope is just over 120 meters in length and 20 meters in diameter. While that dwarfs Goodyear's current, 75-meter Wingfoot One, it's still only half the length of the *Hindenburg*. LTA expects *Pathfinder 1* to carry approximately 4 tonnes of cargo, in addition to its crew, water ballast, and fuel. The airship will have a top speed of 65 knots, or about 120 kilometers per hour—on par with the *Hindenburg*—with a sustained cruise speed of 35 to 40 knots (65 to 75 km/h).

It may not seem much of an advance to be building an airship that flies no faster than the *Hindenburg*. But *Pathfinder 1* carries a lot of new tech that LTA is betting will prove key to an airship resurgence.

For one, airships used to be constructed around riveted aluminum girders, which provided the highest strength-to-weight ratio available at the time. Instead, LTA will be using carbon-fiber tubes attached to titanium hubs. As a result, *Pathfinder 1*'s primary structure will be both stronger and lighter.

Pathfinder 1's outer covering is also a step up from past generations. Airships like the 1930s' *Graf Zeppelin* had coverings made out of doped cotton canvas. The dope painted on the fabric increased its strength and resiliency. But canvas is still canvas. LTA has instead built its outer coverings out of a three-layer laminate of synthetics. The outermost layer is DuPont's Tedlar, which is a polyvinyl fluoride. The middle layer is a loose weave of fire-retardant aramid fibers. The inner layer is polyester. "It's very similar to what's used in a lot of racing sailboats," says Taussig. "We needed to modify that material to make it fire resistant and change a little bit about its structural performance."

LTA Research staff maneuver *Pathfinder 1* while the airship is under construction at the company's Moffett Field facility, near San Francisco.

LTA RESEARCH

But neither the materials science nor the manufacturing advances will take primary credit for LTA's looked-for success, according to Taussig—instead, it's the introduction of electronics. "Everything's electric on Pathfinder," he says. "All the actuation, all the propulsion, all the actual power is all electrically generated. It's a fully electric fly-by-wire aircraft, which is not something that was possible 80 years ago." *Pathfinder 1* has 12 electric motors for propulsion, as well as four tail fins with steering rudders controlled by its fly-by-wire system. (During initial test flights, the airship will be powered by two reciprocating aircraft engines).

There's one other piece of equipment making an appearance on *Pathfinder 1* that wasn't available 80 years ago: lidar. Installed at the top of each of *Pathfinder 1*'s helium gas cells is an automotive-grade lidar. "The lidar can give us a point cloud showing the entire internal hull of that gas cell," says Taussig, which can then be used to determine the gas cell's volume accurately. In flight, the airship's pilots can use that information, as well as data about the helium's purity, pressure, and temperature, to better keep the craft pitched properly and to avoid extra stress on the internal structure during flight.

Although LTA's initial focus is on humanitarian applications, there are other areas where airships might shine one day. "An airship is kind of a 'tweener,' in between sea cargo and air freight," says Taussig. Being fully electric, *Pathfinder 1* is also greener than traditional air- or sea-freight options.

At press time, LTA planned to finish *Pathfinder 1*'s construction late in 2022. That will be followed by ground tests on each of the airship's systems in the first part of 2023. Once the team is satisfied with those tests, they'll move to tethered flight tests and finally untethered flight tests over San Francisco's South Bay later in the year.

The company will also construct an approximately 180-meter-long airship, *Pathfinder 3* at its Akron Airdock facility in Ohio. *Pathfinder 3* won't be ready to fly in 2023, but its development shows LTA's aspirations for an airship renaissance is more than just hot air. ■

BALLOONS VS. HYPERSONIC MISSILES

In a bid for the most MacGyver-worthy defense strategy, the Pentagon has planned a sevenfold increase in spending on hot-air balloons in 2023. These high-flying, low-tech aircraft are already in use for surveillance, hovering at 18,000 to 27,000 meters to track drug runners. The hope is, these floating leviathans will collaborate with satellites to detect hypersonic missiles, like those being developed by Russia and China. As a bonus, the tech onboard the balloons runs on solar power.

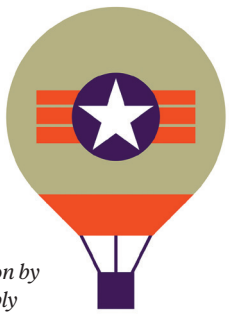


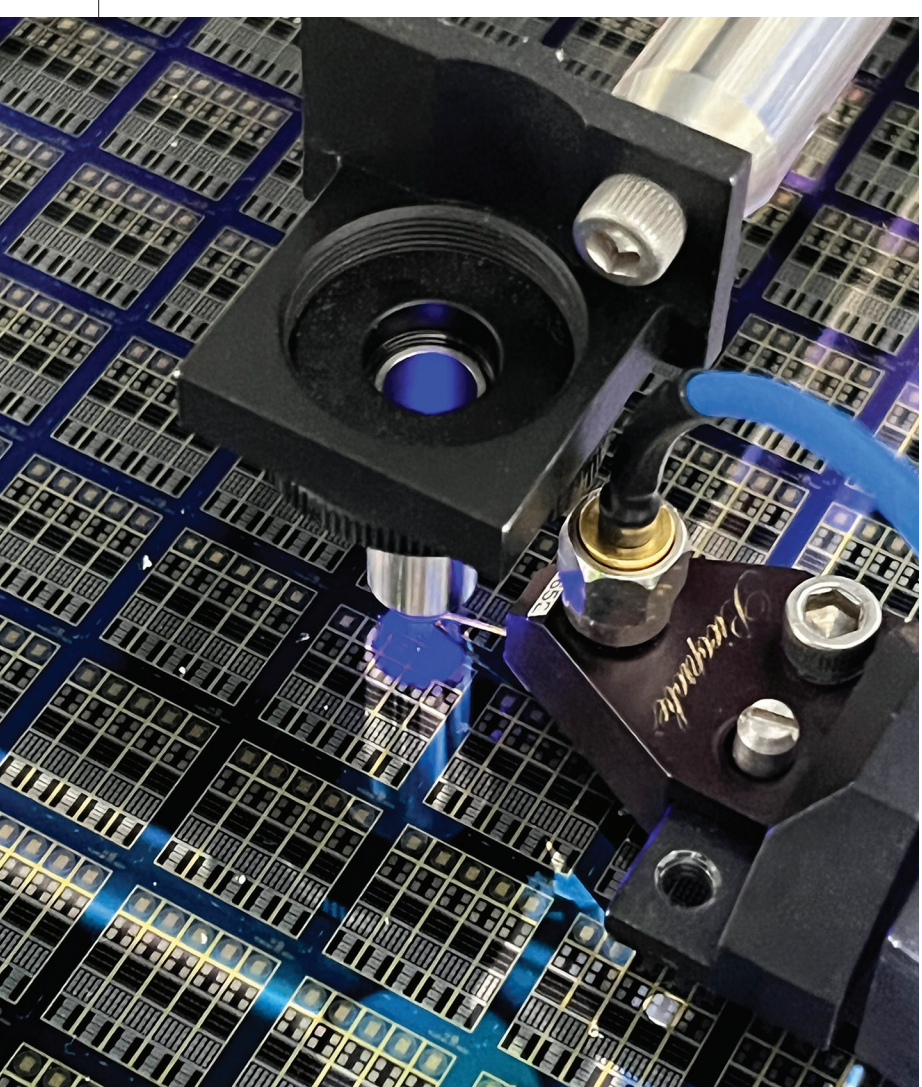
Illustration by Greg Mably

Avicena's blue microLEDs are in a race with Ayar Lab's laser-based system

A Dark (Blue) Horse Emerges to Speed Up Computing

By SAMUEL K. MOORE

If a CPU in Seoul sends a byte of data to a processor in Prague, the information covers most of the distance as light, zipping along with no resistance. But put both those processors on the same motherboard, and they'll need to communicate over energy-sapping copper, which slows the communication speeds possible within computers. Two Silicon Valley startups, Avicena and Ayar Labs, are doing something about that longstanding limit. If they succeed in their attempts to finally bring optical fiber all the way to the processor, it might not just accelerate computing—it might also remake it.



Avicena's microLED chiplets could one day link all the CPUs in a computer cluster together.

AVICENA

Both companies are developing fiber-connected chiplets, small chips meant to share a high-bandwidth connection with CPUs and other data-hungry silicon in a shared package. They are each ramping up production in 2023, though it may be a couple of years before we see a computer on the market with either product.

Ayar Labs, has succeeded at drastically miniaturizing and reducing the power consumption of the kinds of silicon-photonics components used today to sling bits around data centers through optical-fiber cables. That equipment encodes data onto multiple wavelengths of light from an infrared laser and sends the light through a fiber.

Avicena's chiplet couldn't be more different: Instead of infrared laser light, it uses ordinary light from a tiny display made of blue microLEDs. And instead of multiplexing all the optical data so it can travel down a single fiber, Avicena's hardware sends data in parallel through the separate pathways in a specialized optical cable.

Ayar has the weight of history on its side, offering customers a technology similar to what they already use to send data over longer distances. But Avicena, the dark horse in this race, benefits from ongoing advances in the microdisplay industry, which is predicted to grow 80 percent per year and reach

US $123 billion by 2030, fueled by a future full of virtual-reality gear and even augmented-reality contact lenses.

"Those companies are two ends of the spectrum in terms of the risk and innovation," says Vladimir Kozlov, founder and CEO of LightCounting, a telecommunications analysis firm.

Avicena's silicon chiplet, LightBundle, consists of an array of gallium-nitride microLEDs, an equal-size array of photodetectors, and some I/O circuitry to support communication with the processor it feeds with data. Twin 0.5-millimeter-diameter optical cables link the microLED array on one chiplet to the photodetectors on another and vice versa. These cables—similar to the imaging cables in some endoscopes—contain a bundle of hundreds of fiber cores that line up with the on-chip arrays, giving each microLED its own light path.

Besides the existence of this type of cable, Avicena needed two other things to come together, explains Bardia Pezeshki, the company's CEO. "The first one, which I think was the most surprising to anyone in the industry, is that LEDs could be run at 10 gigabits per second," he says. "That is stunning" considering that the state of the art for visible-light communication systems just five years ago was in the hundreds of megahertz. But in 2021, Avicena researchers revealed a version of the microLED they dubbed cavity-reinforced optical micro-emitters, or CROMEs. The devices are microLEDs that have been optimized for switching speed by minimizing capacitance and sacrificing some efficiency at converting electrons to light.

Gallium nitride isn't something that's typically integrated on silicon chips for computing, but thanks to advances in the microLED-display industry, doing so is essentially a solved problem. Seeking bright emissive displays for AR/VR and other things, tech giants such as Apple, Google, and Meta have spent years coming up with ways to transfer already-constructed micrometer-scale LEDs to precise spots on silicon and other surfaces. Now "it's done by the millions every day," says Pezeshki. Avicena itself recently purchased the fab where it developed the CROMEs from its Silicon Valley neighbor Nanosys.

10 Gb/s

The speed at which microLEDs can switch, an improvement from 100s of MHz in 2017

The second component was the photodetector. Silicon isn't good at absorbing infrared light, so the designers of silicon-photonics systems typically compensate by making photodetectors and other components relatively large. But because silicon readily soaks up blue light, photodetectors for Avicena's system need only be a few tenths of a micrometer deep, allowing them to be easily integrated in the chiplet under the imaging-fiber array. Pezeshki credits Stanford's David A.B. Miller with proving, more than a decade ago, that blue-light-detecting CMOS photodetectors were fast enough to do the job.

The combination of imaging fiber, blue microLEDs, and silicon photodetectors leads to a system that in prototypes transmits "many" terabits per second, says Pezeshki. Equally important as the data rate is the low energy needed to move a bit. "If you look at silicon-photonics target values, they are a few picojoules per bit, and these are from companies that are way ahead of us" in terms of commercialization, says Pezeshki. "We've already beaten those records." In a demo, the system moved data using about half a picojoule per bit. The startup's first product, expected in 2023, will not reach all the way to the processor but will aim to connect servers within a data-center rack. A chiplet for chip-to-chip optical links will follow "right on its heels," says Pezeshki.

But there are limits to the ability of microLEDs to move data. Because the LED light is incoherent, it suffers from dispersion effects that restrict it to about 10 meters. Lasers, in contrast, are naturally good at going the distance; Ayar's TeraPHY chiplets have a reach of up to 2 kilometers, potentially disrupting the architecture of supercomputers and data centers even more than Avicena's tech could. They could let computer makers completely rethink their architectures, allowing them to construct "essentially a single computer chip, but building it at rack scale," says Ayar CEO Charlie Wuischpard. The company is ramping up production with its partner GlobalFoundries and is building prototypes with partners in 2023, though these are not likely to be made public, he says.

Kozlov says to expect many more competitors to emerge. Computer makers will want solutions that will "not just help in the next two to three years but will give reliable improvements for decades." After all, the copper connections they are seeking to replace are still improving, too. ■

ONE CHARGER TO RULE THEM ALL

The European Union has adopted a directive that mandates a range of devices charge using USB-C ports. Apple, with its unique lightning port, will be no exception: iPhones, iPads, and other small devices will be forced to migrate to USB-C by 2024. Laptops will have to follow sometime in 2026. This law is the first of its kind anywhere in the world. It's meant to improve convenience for the consumer, as well as cut down on electronics waste generated by different chargers, which is currently responsible for an estimated 11,000 tonnes per year. Several U.S. senators have pushed for similar legislation, so far to no avail.

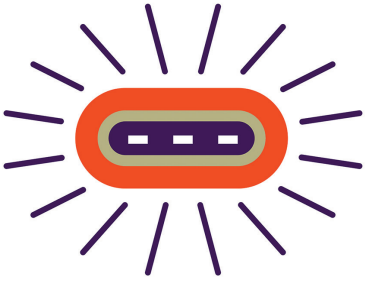


Illustration by Greg Mably

Finally, an eVTOL You Can Buy Soonish

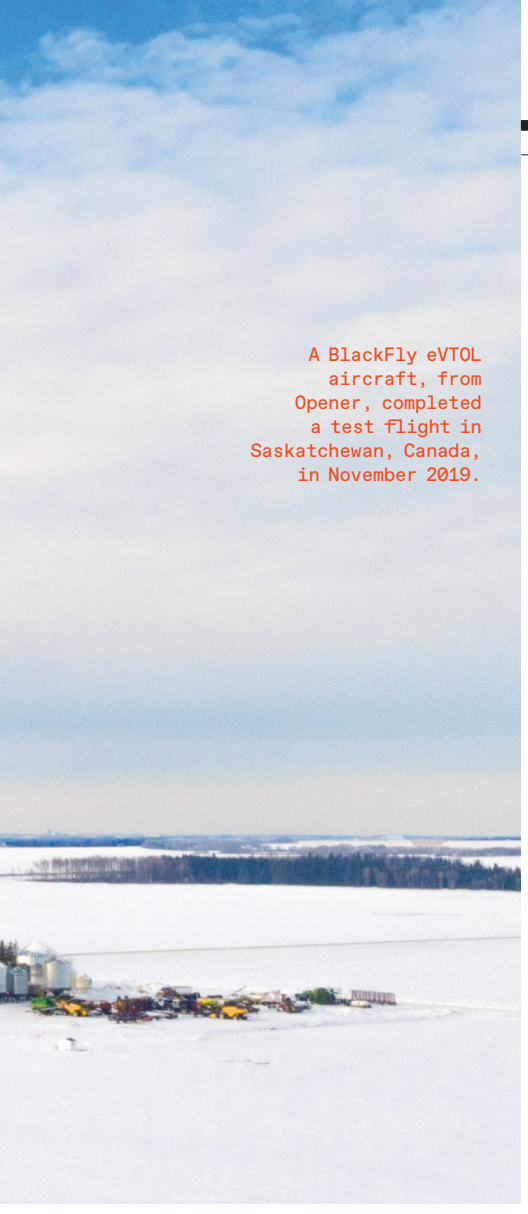
Opener's BlackFly is the first of a radical new class of automated ultralight fliers

By GLENN ZORPETTE

If electric vertical takeoff and landing aircraft do manage to revolutionize transportation, the date of 5 October 2011, may live on in aviation lore. That was the day when a retired mechanical engineer named Marcus Leng flew a home-built eVTOL across his front yard in Warkworth, Ont., Canada, startling his wife and several of his friends.

"So, take off, flew about 6 feet above the ground, pitched the aircraft towards my wife and the two couples that were there, who were behind automobiles for protection, and decided to do a skidding stop in front of them. Nobody had an idea that this was going to be happening," recalls Leng.

But as he looked to set his craft down, he saw a wing starting to dig into his



A BlackFly eVTOL aircraft, from Opener, completed a test flight in Saskatchewan, Canada, in November 2019.

lawn. "Uh-oh, this is not good," he thought. "The aircraft is going to spin out of control. But what instead happened was the propulsion systems revved up and down so rapidly that as the aircraft did that skidding turn, that wing corner just dragged along my lawn exactly in the direction I was holding the aircraft, and then came to a stable landing," says Leng. At that point, he knew that such an aircraft was viable "because to have that sort of an interference in the aircraft and for the control systems to be able to control it was truly remarkable."

It was the second time anyone, anywhere had ever flown an eVTOL aircraft.

Today, some 350 organizations in 48 countries are designing, building, or flying eVTOLs, according to the Vertical Flight Society. These companies are fueled by more than US $7 billion and perhaps as much as $10 billion in startup funding. And yet, 11 years after Leng's flight, no eVTOLs have been delivered to customers or are being produced at commercial scale. None have even been certified by a civil aviation authority in the West, such as the U.S. Federal Aviation Administration or the European Union Aviation Safety Agency.

But 2023 looks to be a pivotal year for eVTOLs. Several well-funded startups are expected to reach important early milestones in the certification process. And the company Leng founded, Opener, could beat all of them by making its first deliveries—which would also be the first for any maker of an eVTOL.

As of late October, the company had built at its facility in Palo Alto, Calif., roughly 70 aircraft—considerably more than are needed for simple testing and evaluation. It had flown more than 30 of them. And late in 2022, the company had begun training a group of operators on a state-of-the-art virtual-reality simulator system.

350

The current number of organizations in 48 countries designing, building, or flying eVTOLs, according to the Vertical Flight Society

Opener's highly unusual, single-seat flier is intended for personal use rather than transporting passengers, which makes it almost unique. Opener intends to have its aircraft classified as an "ultralight," enabling it to bypass the rigorous certification required for commercial-transport and other aircraft types. The certification issue looms as a major unknown over the entire eVTOL enterprise, at least in the United States, because, as the blog Jetlaw.com noted last August, "the FAA has no clear timeline or direction on when it will finalize a permanent certification process for eVTOL."

Opener's strategy is not without risks, either. For one, there's no guarantee that the FAA will ultimately agree that Opener's aircraft, called BlackFly, qualifies as an ultralight. And not everyone is happy with this approach. "My concern is, these companies that are saying they can be ultralights and start flying around in public are putting at risk a $10 billion [eVTOL] industry," says Mark Moore, founder and chief executive of Whisper Aero in Crossville, Tenn. "Because if they crash, people won't know the difference" between the ultralights and the passenger eVTOLs, he adds. "To me, that's unacceptable." Previously, Moore led a team at NASA that designed a personal-use eVTOL and then served as engineering director at Uber's Elevate initiative.

Opener's aircraft is as singular as its business model. It's a radically different kind of aircraft, and it sprang almost entirely from Leng's fertile mind.

"As a kid," he says, "I already envisioned what it would be like to have an aircraft that could seamlessly do a vertical takeoff, fly, and land again without any encumbrances whatsoever." It was a vision that never left him, from a mechanical-engineering degree at the University of Toronto, management jobs in the aerospace industry, starting a company and making a pile of money by inventing a new kind of memory foam, and then retiring in 1996 at the age of 36.

The fundamental challenge to designing a vertical-takeoff aircraft is endowing it with both vertical lift and efficient forward cruising. Most eVTOL makers achieve this by physically tilting multiple large rotors from a vertical rotation axis, for takeoff, to a horizontal one, for cruising. But the mechanism for tilting the rotors must be extremely robust, and therefore it inevitably adds substantial complexity and weight. Such tilt-rotors also entail significant compromises and trade-offs in the size of the rotors and their placement relative to the wings.

Opener's BlackFly ingeniously avoids having to make those trade-offs and compromises. It has two wings, one in front and one behind the pilot. Affixed to each wing are four motors and rotors—and these never change their orientation relative to the wings. Nor do the wings move relative to the fuselage. Instead, the entire aircraft rotates in the air to transition between vertical and horizontal flight.

A BlackFly eVTOL took off on 1 October 2022 at the Pacific Airshow in Huntington Beach, Calif. [left]. Software engineer Bodhi Connolly took a BlackFly for a twilight spin on 29 July 2022, at the EAA AirVenture show in Oshkosh, Wis. [right].

To control the aircraft, the pilot moves a joystick, and those motions are instantly translated by redundant flight-control systems into commands that alter the relative thrust among the eight motor-propellers.

Visually, it's an astounding aircraft, like something from a 1930s pulp sci-fi magazine. It's also a triumph of engineering.

Leng says the journey started for him in 2008, when "I just serendipitously stumbled upon the fact that all the key technologies for making electric VTOL human flight practical were coming to a nexus."

The journey that made Leng's dream a reality kicked into high gear in 2014 when a chance meeting with investor Sebastian Thrun at an aviation conference led to Google cofounder Larry Page investing in Leng's project.

Leng had begun building in his basement in 2010, spending his own money on a mélange of home-built and commercially available components. The motors were commercial units that he modified himself, the motor controllers were German and off the shelf, the inertial-measurement unit was open source and based on an Arduino microcontroller. The batteries were modified model-aircraft lithium-polymer types.

"The main objective behind this was proof of concept," he says. "I had to prove it to myself, because up until that point, they were just equations on a piece of paper. I had to get to the point where I knew that this could be practical."

After his front-yard flight in 2011, there followed several years of refining and rebuilding all of the major components until they achieved the specifications Leng wanted. "Everything on BlackFly is from first principles," he declares.

The motors started out generating 160 newtons (36 pounds) of static thrust. It was way too low. "I actually tried to purchase motors and motor controllers from companies that manufactured those, and I specifically asked them to customize those motors for me, by suggesting a number of changes," he says. "I was told that, no, those changes won't work."

So he started designing his own brushless AC motors. "I did not want to design motors," says Leng. "In the end, I was stunned at how much improvement we could make by just applying first principles to this motor design."

To increase the power density, he had to address the tendency of a motor in an eVTOL to overheat at high thrust, especially during hover, when cooling airflow over the motor is minimal. He began by designing a system to force air through the motor. Then he began working on the rotor of the motor (not to be confused with the rotor wings that lift and propel the aircraft). This is the spinning part of

LEFT: IRFAN KHAN/LOS ANGELES TIMES/GETTY IMAGES; RIGHT: OPENER

a motor, which is typically a single piece of electrical steel. It's an iron alloy with very high magnetic permeability.

By layering the steel of the rotor, Leng was able to greatly reduce its heat generation, because the thinner layers of steel limited the eddy currents in the steel that create heat. Less heat meant he could use higher-strength neodymium magnets, which would otherwise become demagnetized. Finally, he rearranged those magnets into a configuration called a Halbach array. In the end Leng's motors were able to produce 609 newtons (137 lbs.) of thrust.

Overall, the 2-kilogram motors are capable of sustaining 20 kilowatts, for a power density of 10 kilowatts per kilogram, Leng says. It's an extraordinary figure. One of the few motor manufacturers claiming a density in that range is H3X Technologies, which says its HPDM-250 clocks in at 12 kW/kg.

The brain of the BlackFly consists of three independent flight controllers, which calculate the aircraft's orientation and position, based on readings from the inertial-measurement units, GPS receivers, and magnetometers. They also use pitot tubes to measure airspeed. The flight controllers continually cross-check their outputs to make sure they agree. They also feed instructions, based on the operator's movement of the joystick, to the eight motor controllers (one for each motor).

Equipped with these sophisticated flight controllers, the fly-by-wire BlackFly is similar in that regard to the hobbyist drones that rely on processors and clever algorithms to avoid the tricky manipulations of sticks, levers, and pedals required to fly a traditional fixed- or rotary-wing aircraft.

That sophisticated, real-time control will allow a far larger number of people to consider purchasing a BlackFly when it becomes available. In mid-December, Opener had not disclosed a likely purchase price, but in the past the company had suggested that BlackFly would cost as much as a luxury SUV. So who might buy it? CEO Ken Karklin points to several distinct groups of potential buyers who have little in common other than wealth.

CONTINUED ON P. 57

Eleven years after Leng's flight, no eVTOLs have been delivered to customers or are being produced at commercial scale.

SEA-MONSTER-PROOF INTERNET

The initial segment of what will be the first underwater fiber-optic link to skirt the North Pole, connecting Japan and Europe, will light up in early 2023. This stretch, called Iris, will link Iceland to Ireland. In subsequent years, the Far North Fiber project will lay down a cable through the Northwest Passage, connecting Iceland to Greenland, then Canada, Alaska, and finally Japan. Far North Fiber will help increase the geographic diversity of the world's fiber-optic network; currently, submarine cables are laid along a few well-trodden routes, leaving the network vulnerable to local hazards, like ship anchors, earthquakes, or fiber-eating sea monsters.

Illustration by Greg Mably

The Robo-01 autonomous electric car shows off its butterfly doors at a reveal to the media in Beijing, in June 2022.

TINGSHU WANG/REUTERS/ALAMY

Baidu and Geely Will Mass-Produce an Autonomous EV

The Chinese tech giants aim for a fully self-driving car

By CRAIG S. SMITH

Last October, a startup called Jidu Automotive, backed by Chinese AI giant Baidu and Chinese carmaker Geely, officially released an autonomous electric car, the Robo-01 Lunar Edition. In 2023, the car will go on sale.

At roughly US $55,000, the Robo-01 Lunar Edition is a limited edition, cobranded with China's Lunar Exploration Project. It has 2 lidars, 5 millimeter-wave radars, 12 ultrasonic sensors, and 12 high-definition cameras. It is the first vehicle to offer on-board, AI-assisted voice recognition, with spoken responses returned within 700 milliseconds, thanks to the Qualcomm Snapdragon 8295 chip.

"It's a car, and, even more so, a robot," said Jidu CEO Joe Xia, during the live-streamed unveiling of the car (as translated from the Mandarin by CNBC). He added that it "can become the standard for self-driving cars."

But just how autonomous the car is remains to be seen: In January 2022, Baidu and Jidu said the car would have Level 4 autonomous-driving capability, which does not require a human driver to control the vehicle. But the press release at the car's launch made no mention of Level 4, saying only that the car offered "high-level autonomous driving."

The blurred language may have been dictated by lawyers. China has yet to establish laws or regulations governing autonomous vehicles for the consumer market. For the time being, a driver must remain in control of the car. In September 2022, Baidu cofounder and CEO Robin Li noted that lower levels of autonomy shield car compa-

40%

Fraction of China's new-vehicle sales forecast to be fully autonomous in 2040.

nies from liability in the event of a crash, because the driver is expected to be in control. With Level 4, the manufacturer of the car or the operator of the "robotaxi" service using the car would be to blame.

Nonetheless, the Robo-01 launch signals a dramatic shift in the automotive industry, which has been slow to adopt electric cars and even slower to embrace autonomy. No other consumer car on the market yet offers Level 4 autonomy. Tesla's Full Self Driving ability, despite its fancy name and the pronouncements of its CEO, is only Level 2, or "partial automated driving" under the definition of SAE International (formerly the Society of Automotive Engineers). Other autonomous-vehicle makers, including Tesla, are collecting data from mass-produced L2 vehicles to train L4 algorithms.

Meanwhile, Mercedes-Benz is offering its Drive Pilot Level 3 autonomous-driving system on S-Class and EQS sedans in Germany. Level 3 handles all aspects of driving, but it requires that the driver remain ready to regain control if requested. Drivers need not keep their eyes on the road, but Drive Pilot will disengage if the driver's face is obscured.

That raises the question of what Robo-01 can do that the Mercedes Drive Pilot cannot. And what features will Robo-01 use to keep drivers' hands on the wheel, as required under current Chinese law? Answers to those questions may have to wait until Robo-01 ships.

Regardless of the car's official autonomy designation, Baidu has billed its self-driving package, Apollo, as having Level 4 capabilities. That includes what the company calls a Point-to-Point Autopilot, designed to handle highway, city street, and parking scenarios. Jidu is conducting further tests in Beijing and Shanghai to ensure that its Point-to-Point Autopilot will cover all major cities in China.

Chinese regulations do allow Level 4 in robotaxis that operate within designated geofenced areas, and Apollo has already shown what it can do in Baidu's Apollo Go robotaxis, which have provided more than 1 million rides in at least 10 cities across China. Baidu recently unveiled its latest autonomous robotaxi, the Level 4 Apollo RT6, which has a detachable steering wheel. The absence of a steering wheel is a statement in itself, and it frees up cabin space for extra seating or even desktops, gaming consoles, and vending machines.

"It's a car, and, even more so, a robot."
—JOE XIA, CEO OF JIDU

China could well become the world's largest market for autonomous vehicles, with fully autonomous vehicles accounting for more than 40 percent of the country's new vehicle sales in 2040, and 12 percent of the vehicle installed base, according to global consulting firm McKinsey.

In 2018, China's Ministry of Industry and Information Technology, together with the Ministry of Public Security and the Ministry of Transportation, published standards for setting up road-test facilities for intelligent automobiles. Soon after, provinces and cities across China began setting up their own road-testing facilities.

Of the many Chinese companies already preparing to enter the autonomous-vehicle market, Baidu is the biggest player. Its Apollo open-source software-development platform launched in 2017. Two years later, the company was granted the first Level 4 road-test licenses in the country. More recently it received fully driverless permits in Wuhan and Chongqing, making Baidu the only company of its kind in China to provide ride-hailing services without any human drivers present in the car, as Waymo does in Phoenix and Cruise does in San Francisco. Meanwhile, its Abolong L4 Autonomous Bus is operating commercially in enclosed campuses in at least 24 Chinese cities.

The Robo-01 is powered by a 100-kilowatt-hour lithium battery from Chinese battery manufacturer Contemporary Amperex Technology Co., or CATL. It can accelerate from 0 to 60 miles per hour (97 kilometers per hour) in about 4 seconds and can go 600 km on a charge.

So, the car can drive far, and it can drive fast. But can it drive itself? We'll find out in 2023. ■

NASCAR MAY LEAN ELECTRIC

According to documents leaked earlier this year, auto-racing giant NASCAR plans to debut a prototype electric vehicle (EV) ahead of its season-opening race in February 2023. This prototype, the documents suggest, will then be used in an EV racing series later in the year. The series would consist of two races lasting 30 minutes apiece, with no battery swaps or charging allowed. This information, although unconfirmed, would be in line with NASCAR's previously stated plans to test out opportunities in the EV space. Amidst much pressure to move toward electric, NASCAR maintains that entertainment value for its fans is the top priority.

Illustration by Greg Mably

China's New Breeder Reactors May Produce More Than Just Watts

They could also make weapons-grade plutonium

BY PRACHI PATEL

Jutting out from the coast of China's Fujian province, Changbiao Island may seem small and unremarkable. It is anything but. This is where the China National Nuclear Corp. is building two fast-neutron nuclear breeder reactors, the first of which is slated to connect to the grid in 2023, the second in 2026. So China could start producing weapons-grade plutonium there very soon.

They are called breeder reactors because they produce more nuclear fuel than they consume. According to Chinese authorities, the ones on Changbiao are civilian power reactors, designed to generate 600 megawatts of electricity each, which amounts to a little more than 1 percent of the total capacity of China's nuclear-power sector. But each reactor could also yield up to 200 kilograms of weapons-grade plutonium each year, enough for about 50 nuclear warheads—which is making nuclear-arms-control experts in Western countries nervous.

"China is in the middle of a big buildup of its nuclear-weapon arsenal," says Frank von Hippel, a physicist and nuclear-policy expert at Princeton University. "My belief is that one of the purposes of these reactors is to produce weapons-grade plutonium for that buildup."

Fast breeder reactors date back more than half a century, when the global nuclear community thought there wouldn't be enough uranium fuel available for the nuclear-power industry. Natural uranium is composed of only 0.7 percent uranium 235 (U-235), which can support the fission reactions needed for generating power. The rest is U-238, which cannot sustain a chain reaction. But when bombarded with neutrons, U-238 is readily transformed into an isotope that can: plutonium-239.

Breeder reactors use plutonium as the fissile fuel in the core, which is surrounded by a blanket rich in U-238. Fast neutrons—that is, ones with 1 megaelectron-volt or more of kinetic energy—split the plutonium atoms, releasing secondary neutrons that are captured by the U-238 and convert some of that U-238 into plutonium. Liquid sodium is used as a coolant because it does not slow down neutrons as much as water does. Weapons-grade plutonium can be separated chemically from the blanket.

200 kg

Yield of each reactor, per year, of weapons-grade plutonium, enough for about 50 nuclear warheads

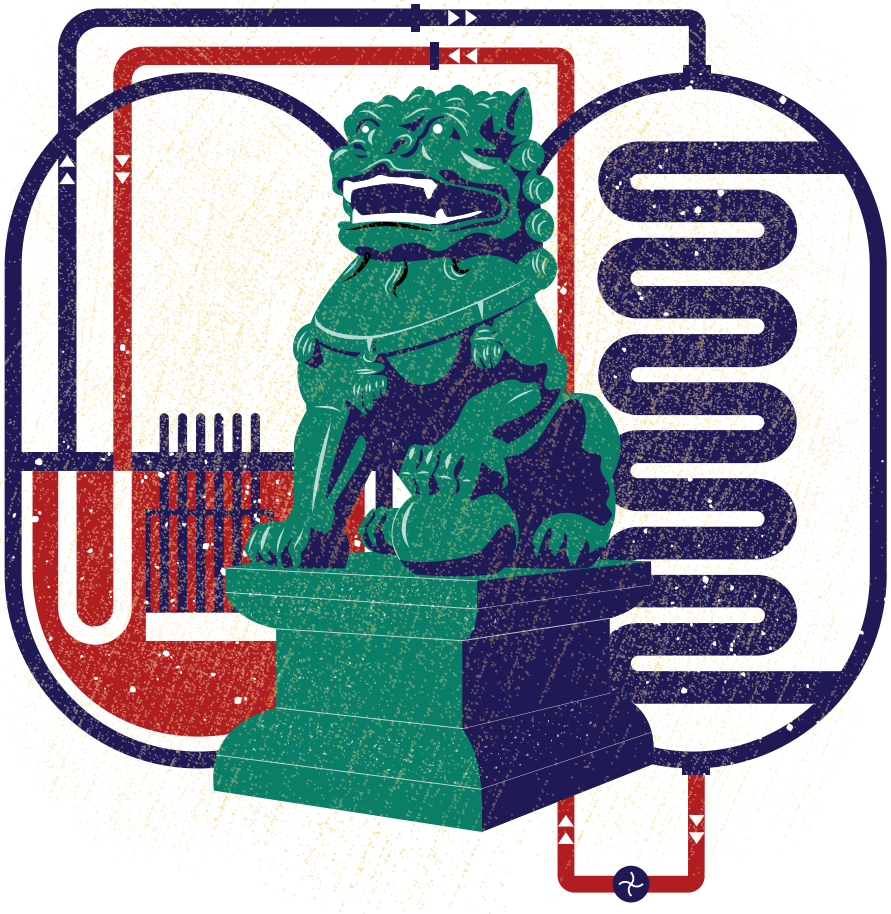
While many countries explored the possibility of using fast breeder reactors early on, only one of the breeder reactors built in France, Germany, the United Kingdom, or the United States survived into the 21st century before it, too, was shut down. Japan also developed a fast breeder power reactor, one that proved to be a costly mistake, prompting a decision in 2016 to decommission it.

Not so in China, India, and Russia. India has had a breeder-reactor prototype under construction for about two decades, von Hippel says. Starting even earlier, Russia has built two fast breeder reactors, which are still operating today. But Russia has decided not to build another one until the 2030s, because they are more expensive than conventional water-cooled reactors.

The new breeder reactors in China, meanwhile, are demonstration projects, the second step in a three-step program to develop fast breeder reactors to reduce the country's dependence on coal. The first step was a 20-MW experimental fast breeder reactor near Beijing, which was begun in 2000 but took many years to complete and connect to the grid. The country will soon decide whether to continue to the third step of building a commercial 1,000-MW breeder reactor. The China National Nuclear Corp. did not respond to inquiries from *IEEE Spectrum* about its plans.

On its own, building a fast breeder reactor is not necessarily a signal that a country intends to produce nuclear weapons, says Jake Hecla, a graduate student in nuclear engineering at the University of California, Berkeley. But the reactors slated for Changbiao are viewed with suspicion in the West, particularly after the recent discovery that China is constructing missile-silo fields in three locations.

China already has between 3 and 5 tonnes of plutonium for warheads, Hecla says. And



they are building 250 additional silos. "So they likely need more plutonium," he says. "One way of doing this would be to create civilian infrastructure that is dual use, and this fast breeder program is perfect for that. If China flipped on old plutonium processing reactors, the international response would be strong and negative. This provides a way to get around that."

An added concern is that China stopped voluntarily disclosing its civilian plutonium stockpiles to the International Atomic Energy Agency in 2018. Other nations with plutonium stockpiles, such as Japan, France, and the United States, "work with the international community to disclose their plutonium stockpiles, providing reassurance that the material is not being misused," says Hecla.

These concerns are valid in light of the expansion of China's nuclear arsenal and the modernization of its nuclear weapons, says Hui Zhang, an expert on China's nuclear policies at Harvard University. But, he points out, there are more straightforward ways to produce weapons-grade plutonium.

"Direct plutonium production could make much more fuel each year," says Zhang. "Because China is already a nuclear state, if they really wanted to build up [their] nuclear-weapon arsenal, it would've been better to dedicate a plutonium fast breeder reactor for that purpose, not to build a reactor for civilian purposes."

But no matter how they intend to do it, if Chinese weapons builders are trying to catch up to the United States, which has nearly 88 tonnes of plutonium, they still have a long road ahead. ■

CHINA'S GOT HYDRO

China is in the midst of a gigantic buildup of hydro-energy capabilities. The world's largest station for pumped-energy storage—a technique that stores energy by pumping it uphill to a reservoir—is set to complete phase two of its construction in 2023. The station, called Fengning and located about 200 kilometers north of Beijing, will store up to 40 gigawatt-hours of energy, and help keep the grid on clean energy when the wind isn't blowing or the sun isn't shining. Separately, the Lianghekou hydropower station in Tibet is also set to be fully operational in 2023, and is expected to generate a whopping 11 terawatt-hours of electricity annually (roughly the energy consumption of Lithuania). These massive construction projects are intended to help China meet its goal of going carbon neutral by 2060.

ICON ART BY GREG MABLY

Illustration by MCKIBILLO

Economics Drives a Ray-Gun Resurgence

Lasers, cheaper by the shot, should work well against drones and cruise missiles

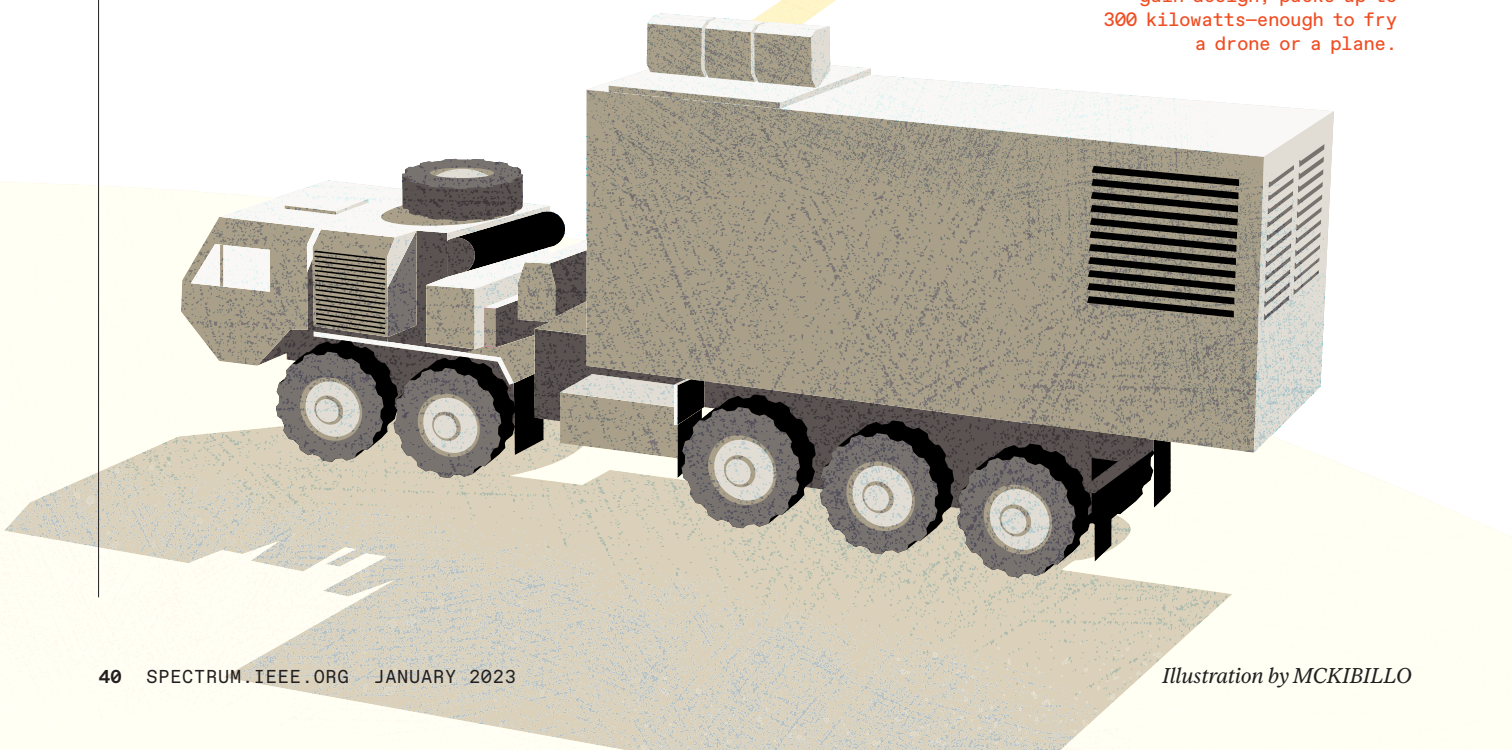
BY PHILIP E. ROSS

The technical challenge of missile defense has been compared with that of hitting a bullet with a bullet. Then there is the still tougher economic challenge of using an expensive interceptor to kill a cheaper target—like hitting a lead bullet with a golden one.

Maybe trouble and money could be saved by shooting down such targets with a laser. Once the system is designed, built, and paid for, the cost per shot would be low. Such considerations led planners at the Pentagon to seek a solution from Lockheed Martin, which has just delivered a 300-kilowatt laser to the U.S. Army. The new weapon combines the output of a large bundle of fiber lasers of varying frequencies to form a single beam of white light. This laser has been undergoing tests in the lab, and it should see its first field trials sometime in 2023. General Atomics, a military contractor in San Diego, is also developing a laser of this power for the Army based on what's known as the distributed-gain design, which has a single aperture.

Both systems offer the prospect of being inexpensive to use. The electric bill itself would range "from US $5 to $10," for a pulse lasting a few seconds, says Michael Perry, the vice president in charge of laser systems for General Atomics.

Why are we getting ray guns only now, more than a century after H.G. Wells imagined them in his sci-fi novel *The War of the Worlds*? Put it down partly to the rising demand



The General Atomics laser, based on the distributed-gain design, packs up to 300 kilowatts—enough to fry a drone or a plane.

Illustration by MCKIBILLO

for cheap antimissile defense, but it's mainly the result of technical advances in high-energy lasers.

The old standby for powerful lasers employed chemical reactions in flowing gas. That method was clumsy, heavy, and dangerous, and the laser itself became a flammable target for enemies to attack. The advantage was that these chemical lasers could be made immensely powerful, a far cry from the puny pulsed ruby lasers that wowed observers back in the 1960s by punching holes in razor blades (at power levels jocularly measured in "gillettes").

By 2014, fiber lasers had reached the point where they could be considered for weapons, and one 30-kW model was installed on the USS *Ponce*, where it demonstrated the ability to destroy speedboats and small drones at relatively close range. The 300-kW fiber lasers being employed now in the two Army projects emit about 100 kW in optical power, enough to burn through much heftier targets (not to mention quite a few gillettes) at considerable distances.

"A laser of that class can be effective against a wide variety of targets, including cruise missiles, mortars, UAVs, and aircraft," says Perry. "But not reentry vehicles [launched by ballistic missiles]." Those are the warheads, and to ward them off, he says, you'd probably have to hit the rocket when it's still in the boost phase, which would mean placing your laser in orbit. Laser tech is still far from performing such a feat.

Even so, these futuristic weapons will no doubt find plenty of applications in today's world. Israel made news in April by field-testing an airborne antimissile laser called Iron Beam, a play on the name Iron Dome, the missile system it has used to down rockets fired from Gaza. The laser system, reportedly rated at about 100 kW, is still not in service and hasn't seen combat, but one day it may be able to replace some, if not all, of Iron Dome's missiles with photons. Other countries have similar capabilities, or say they do. In May, Russia said it had used a laser to incinerate a Ukrainian drone from 5 kilometers away, a claim that Ukraine's president, Volodymyr Zelenskyy, derided.

Not all ray guns must be lasers, though. In March, *Taiwan News* reported that Chinese researchers had built a microwave weapon that in principle could be placed in orbit from where its 5-megawatt pulses could fry the electronic heart of an enemy satellite. But making such a machine in the lab is quite different from operating it in the field, not to mention in outer space, where supplying power and removing waste heat constitute major problems.

US $5

The cost of electricity required to down an aircraft

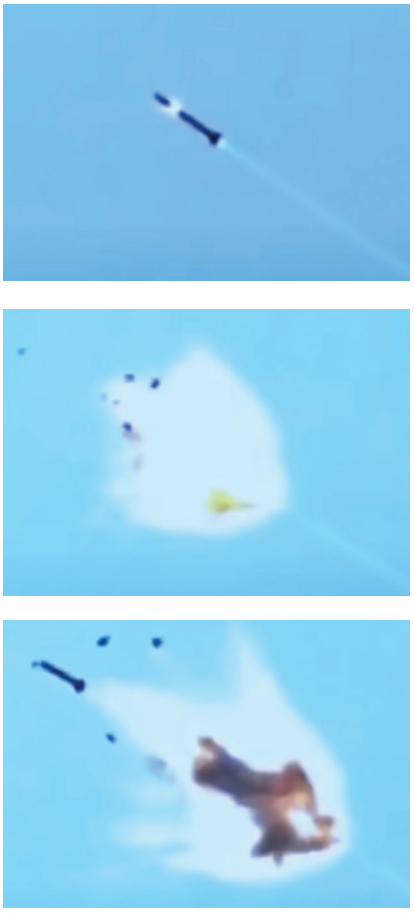
Because lasers may perform poorly in bad weather, they can't be relied on by themselves to defend critically important targets. They must instead be paired with kinetic weapons—missiles or bullets—to create a layered defense system.

"With lasers, if you can see it, you can kill it; typically rain and snow are not big deterrents," says Robert Afzal, an expert on lasers at Lockheed Martin. "But a thundercloud—that's hard."

Afzal says that the higher up a laser is placed, the less interference it will face, but there is a trade-off. "With an airplane you have the least amount of resources—least volume, least weight—that are available to you. On a ship, you have a lot more resources available, but you're in the maritime atmosphere, which is pretty hazy, so you may need a lot more power to get to the target. And the Army is in between: It deals with closer threats, like rockets and mortars, and they need a deep magazine, because they deal with a lot more targets."

In every case, the point is to use expensive antimissile missiles only when you must. Israel opted to pursue laser weapons in part because its Iron Dome missiles cost so much more than the unguided, largely homemade rockets they defend against. Some of the military drones that Russia and Ukraine are now flying wouldn't break the budget of the better-heeled sort of hobbyist. And it would be a Pyrrhic victory indeed to shoot them from the sky with projectiles so costly that you went broke. ■

"With lasers, if you can see it, you can kill it."
—ROBERT AFZAL, LOCKHEED MARTIN



A missile is destroyed by a 2013 low-power version of Lockheed Martin's fiber laser.

LOCKHEED MARTIN

A Cryptocurrency for the Masses or a Universal ID?

Worldcoin aims to scan all the world's eyeballs

By EDD GENT

In a college classroom in the Indian city of Bangalore last August, Moiz Ahmed held up a volleyball-size chrome globe with a glass-covered opening at its center. Ahmed explained to the students that if they had their irises scanned with the device, known as the Orb, they would be rewarded with 25 Worldcoins, a soon-to-be released cryptocurrency. The scan, he said, was to make sure they hadn't signed up before. That's because Worldcoin, the company behind the project, wants to create the most widely and evenly distributed cryptocurrency ever by giving every person on the planet the same small allocation of coins.

Some listeners were enthusiastic, considering the meteoric rise in value of cryptocurrencies like Bitcoin since they launched. "I found it to be a very unique opportunity," said Diksha Rustagi. "You can probably earn a lot from Worldcoin in the future." Others were more cautious, including a woman who goes by Chaitra R, who hung at the back of the classroom as her fellow students signed up. "I have a lot of doubts," she said. "We would like to know how it's going to help us."

Those doubts may be warranted. The 5-minute pitch from Ahmed, a contractor hired to recruit users,

Illustration by MCKIBILLO

focused on Worldcoin's potential as a digital currency, but the project's goals have morphed considerably since its inception. Over the past year, the company has developed a system for third parties to leverage its massive registry of "unique humans" for a host of identity-focused applications.

Worldcoin CEO Alex Blania says the company's technology could solve one of the Web's thorniest problems—how to prevent fake identities from distorting online activity, without compromising people's privacy. Potential applications include tackling fake profiles on social media, distributing a global universal basic income (UBI), and empowering new forms of digital democracy.

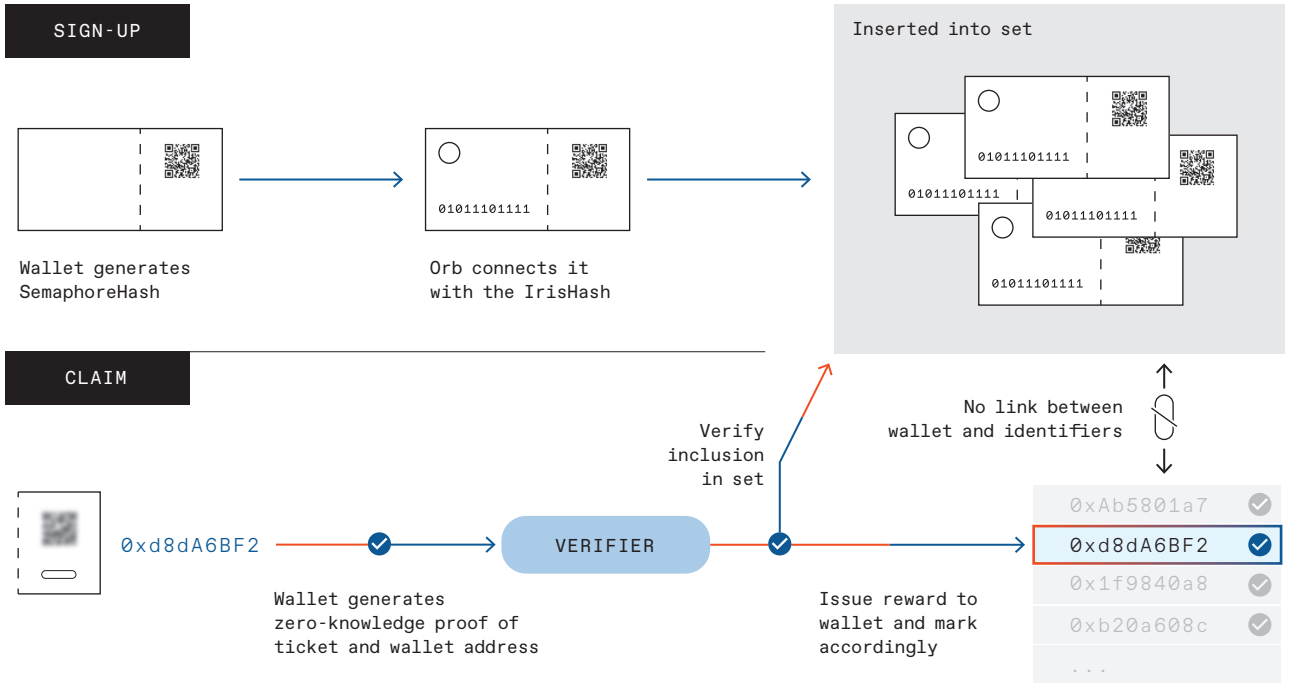
But Worldcoin's biometric-centered approach is facing considerable pushback. The nature of its technology and the lack of clarity about how it will be used are fueling concerns around privacy, security, and transparency. Questions are also being raised over whether Worldcoin's products can live up to its ambitious goals.

So far, Worldcoin has signed up more than 700,000 users in some 25 countries, including Chile, France, and Kenya. In 2023 it plans to fully launch the project and hopes to scale up its user base rapidly. Many people will be watching the company during this make-or-break year to see how these events will unfold. Will Worldcoin succeed in reimagining digital identity, or will it collapse, like so many buzzy cryptocurrencies that have come before?

In early 2020, Blania started working with Worldcoin cofounders Sam Altman, former president of the legendary Silicon Valley incubator Y Combinator, and Max Novendstern, who previously worked at the financial-technology company Wave. The question driving them was a simple one, Blania says. What would happen if they gave every person on the planet an equal share of a new cryptocurrency?

Their thesis was that the network effects would make the coin far more useful than previous cryptocurrencies—the more people who hold it, the easier it would be to send and receive payments with it. It could also boost financial inclusion for millions around the world without access to traditional banking, says Blania. And, if the coins increase in value (as have other cryptocurrencies like Bitcoin and Ethereum), that trend could help redistribute global wealth.

Most ambitiously, the founders envisaged Worldcoin as a global distribution network for UBI—a radical approach to social welfare in which every citizen receives regular cash payments to cover their basic needs. The idea has become popular in Silicon Valley as an antidote to the job-destroying effects of automation, and it has been tried out in locations including California, Finland, and Kenya. When the Worldcoin project was unveiled in October 2021, Altman told



WORLDCOIN

Worldcoin will manage two different processes: signing up users and letting them claim the promised amount of the cryptocurrency as a reward for signing up. Signing up involves scanning users' irises and keeping records that connect those scans with their digital wallets. Claiming a reward requires verification that the user has indeed signed up, which can be done in a way that doesn't reveal any information about the user other than that they are signed up.

THE FRENCH NUKE UP

Over a decade behind schedule and billions of dollars over budget, France's next-generation nuclear reactor in Flamanville is finally expected to get fueled up in early 2024. The plant will be only the world's fourth EPR reactor—a third-generation pressurized water design that's meant to be safer and more efficient than its predecessors. The project has been plagued by safety concerns, engineering missteps, and most recently pandemic supply chain issues. But now, Électricité de France (EDF) says they are in the final stretch. The plant could not come too soon to help decrease Europe's reliance on Russian oil and gas.

Wired that the coin could one day be used to fairly distribute the enormous profits generated by advanced artificial-intelligence systems.

To ensure even distribution of coins, Worldcoin needed a sign-up process that guaranteed that each person could register only once. Blania says the team didn't want to tie the cryptocurrency to government IDs due to privacy risks, and they eventually decided that only biometric iris scans could scale into the billions. Given the sensitivity of biometric data, the team knew that privacy protections had to be paramount. Their solution is a protocol based on Proof-of-Personhood (PoP)—a complex combination of custom hardware, machine learning, cryptography, and blockchain technology that Blania says can assign everyone a unique digital identity with complete anonymity.

56%

Fraction of adult Nigerians who trade in cryptocurrency monthly, according to one 2022 study

The Orb is central to this approach. Behind its gleaming surface is a custom optical system that captures high-definition iris scans. To sign up for Worldcoin, enrollees download the company's app onto their smartphones, where it creates a pair of linked cryptographic keys: a shareable public key and a private key that remains hidden on the user's device. The public key is used to generate a QR code that the Orb reads before scanning users' irises. The company says it has invested considerable effort into making Orbs resistant to spoofing sign-ups with modified or fake irises.

The scan is then converted into a string of numbers known as a hash via a one-way function, which makes it nearly impossible to re-create the image even if the hash is compromised. The Orb sends the iris hash and a hash of the user's public key to Worldcoin's servers in a signed message. The system checks the iris hash against a database to see whether the person has signed up before, and if not, it's added to the list. The public-key hash is added to a registry on the company's blockchain.

The process for claiming the user's free Worldcoins relies on a cryptographic technique known as a zero-knowledge proof (ZKP), which lets a user prove knowledge of a secret without revealing it. The app's wallet uses an open-source protocol to generate a ZKP showing that the holder's private key is linked to a public-key hash on the blockchain, without revealing which one. That way, Worldcoin won't know which public key is associated with which wallet address. Once this linkage is verified by the company's servers, the tokens are

LEFT: WORLDCOIN; RIGHT: EDD GENT

Illustrations by Greg Mably

People queue up to have their irises scanned at an outdoor sign-up event in Indonesia [left]. Worldcoin's scanning device, called the Orb, resembles a giant eyeball, as seen in this image from a sign-up session in India [right].

sent to the wallet. The ZKP also includes a string of numbers unique to each user called a nullifier, which shows whether they've tried to claim their coins before without revealing their identity.

It didn't take long for Worldcoin to realize that its identity system could have broader applications. According to Blania, the first to spot the potential was Chris Dixon, a partner at the venture capital firm Andreessen Horowitz, which led the first investment round in Worldcoin. Blania says that about seven months after the team started work on the project, Dixon told them, "This is super interesting tech, but I think you don't understand what a big deal it actually is."

On today's Internet, most activities flow through centralized platforms like Amazon, Facebook, and PayPal. Blockchain technology could in theory remove these middlemen, instead using a decentralized networks of volunteers to regulate such functions as online payments, social media, ride-sharing platforms, and many other types of services—a vision for the future of the Internet dubbed Web3.

But decentralization also enables new kinds of manipulation, including sybil attacks, named after the 1973 book *Sybil*, about a woman with multiple personalities. The anonymity of the Internet means it's easy to create multiple identities that let attackers gain disproportionate influence over decentralized networks. That's why cryptocurrencies today require members to carry out complex mathematical puzzles or stake large chunks of their money if they want to contribute to core activities like verifying transactions. But that means control of these networks often boils down to how many high-powered computer chips you can afford or how much crypto you hold.

A method to ensure that every member of a network has just one identity could solve the sybil problem in a much more equitable way. And a unique digital ID could have applications beyond Web3, says Tiago Sada, head of product at Worldcoin, such as preventing bot armies on social media, replacing credit-card or government-ID verification to access online services, or even facilitating democratic governance over the Web. Toward the end of last year, Sada says, Worldcoin started work on a new product called World ID—a software-development kit that lets third parties accept ZKPs of "unique humanness" from Worldcoin users.

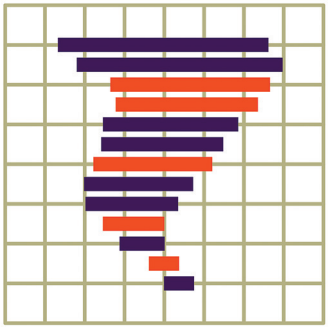
"A widely adopted PoP changes the nature of the Internet completely," says Sada. "Once you have sybil resistance, this idea of a unique person [on a blockchain], then it just gives you an order of magnitude more things you can do."

Despite the startup's growing focus on World ID, Blania insists its ambitions for the Worldcoin cryptocurrency haven't diminished. "There is no token that has more than 100 million users," he says. Worldcoin could have billions. "And really no one knows what the explosion of innovation will be if that actually happens."

CONTINUED ON P. 56

HURRICANE-MODEL OVERHAUL

U.S. hurricane tracking-and-prediction models will get a much needed upgrade ahead of the 2023 season. The U.S. model has been lagging in accuracy behind Europe's version, a problem that first became evident during Hurricane Sandy in 2012. Now, the U.S. National Oceanic and Atmospheric Administration has put a new set of supercomputers into operation to power the next generation of modeling. The improvements will include higher resolution, more-realistic physics to represent clouds and precipitation, a larger number of simulations, and more-effective use of observational data.



IBM's Quantum Leap

The company will take quantum tech past the 1,000-qubit mark in 2023

By CHARLES Q. CHOI

IBM's Condor, the world's first universal quantum computer with more than 1,000 qubits, is set to debut in 2023. The year is also expected to see IBM launch Heron, the first of a new flock of modular quantum processors that the company says may help it produce quantum computers with more than 4,000 qubits by 2025.

While quantum computers can, in theory, quickly find answers to problems that classical computers would take eons to solve, today's quantum hardware is still short on qubits, limiting its usefulness. Entanglement and other quantum states necessary for quantum computation are infamously fragile, being susceptible to heat and other disturbances, which makes scaling up the number of qubits a huge technical challenge.

Nevertheless, IBM has steadily increased its qubit numbers. In 2016, it put the first quantum computer in the cloud for anyone to experiment with—a device with 5 qubits, each a superconducting circuit cooled to near-absolute zero. In 2019, the company created the 27-qubit Falcon; in 2020, the 65-qubit Hummingbird; in 2021, the 127-qubit Eagle, the first quantum processor with more than 100 qubits; and in 2022, the 433-qubit Osprey.

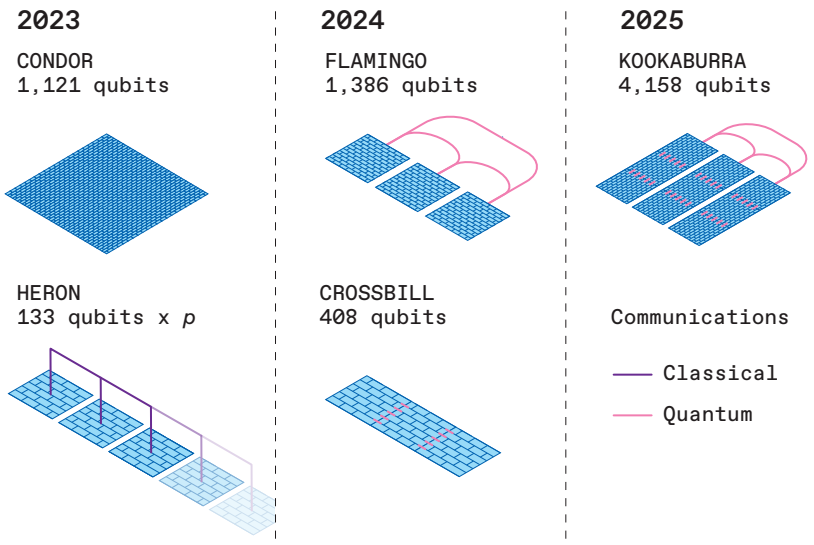
Other quantum computers have more qubits than does IBM's 1,121-qubit Condor processor—for instance, D-Wave Systems unveiled a 5,000-qubit system in 2020. But D-Wave's computers are specialized machines for solving optimization problems, whereas Condor will be the world's largest general-purpose quantum processor.

"A thousand qubits really pushes the envelope in terms of what we can really integrate," says Jerry Chow, IBM's director of quantum infrastructure. By separating the wires and other components needed for readout and control onto their own layers, a strategy that began with Eagle, the researchers say they can better protect qubits from disruption and incorporate larger numbers of them. "As we scale upwards, we're learning design rules like 'This can go over this; this can't go over this; this space can be used for this task,'" Chow says.

With only 133 qubits, Heron, the other quantum processor IBM plans for 2023, may seem modest compared with Condor. But IBM says its upgraded architecture and modular design herald a new strategy for developing powerful quantum computers. Whereas Condor uses a fixed-coupling architecture to connect its qubits, Heron will use an architecture with tunable couplings, which add Josephson junctions between the superconducting loops that carry the qubits. This strategy reduces crosstalk between qubits, boosting processing speed and reducing errors. (Google is already using such an architecture with its 53-qubit Sycamore processor.)

A researcher at IBM's Thomas J. Watson Research Center examines some of the quantum hardware being constructed there.

CONNIE ZHOU/IBM



IBM expects to build quantum computers of increasing complexity over the next few years, starting with those that use the Condor processor or multiple Heron processors in parallel.

In addition, Heron processors are designed for real-time classical communication with one another. The classical nature of these links means their qubits cannot entangle across Heron chips for the kind of boosts in computing power for which quantum processors are known. Still, these classical links enable "circuit knitting" techniques in which quantum computers can get assistance from classical computers.

For example, using a technique known as "entanglement forging," IBM researchers found they could simulate quantum systems such as molecules using only half as many qubits as is typically needed. This approach divides a quantum system into two halves, models each half separately on a quantum computer, and then uses classical computing to calculate the entanglement between both halves and knit the models together.

While these classical links between processors are helpful, IBM intends eventually to replace them. In 2024, the company aims to launch Crossbill, a 408-qubit processor made from three microchips coupled together by short-range quantum communication links, and Flamingo, a 462-qubit module it plans on uniting by roughly 1-meter-long quantum communication links into a 1,386-qubit system. If these experiments in connectivity succeed, IBM aims to unveil its 1,386-qubit Kookaburra module in 2025, with short- and long-range quantum-communication links combining three such modules into a 4,158-qubit system.

IBM's methodical strategy of "aiming at step-by-step improvements is very reasonable, and it will likely lead to success over the long term," says Franco Nori, chief scientist at the Theoretical Quantum Physics Laboratory at the Riken research institute in Japan.

4,158

Number of qubits that should be available in a 2025 IBM quantum computer that will use three 1,386-qubit modules

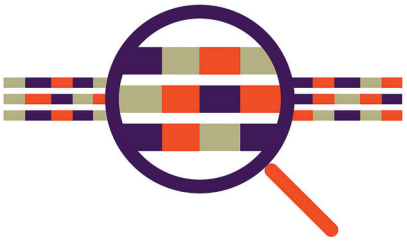
In 2023, IBM also plans to improve its core software to help developers use quantum and classical computing in unison over the cloud. "We're laying the groundwork for what a quantum-centric supercomputer looks like," Chow says. "We don't see quantum processors as fully integrated but as loosely aggregated." This kind of framework will grant the flexibility needed to accommodate the constant upgrades that quantum hardware and software will likely experience, he explains.

In 2023, IBM plans to begin prototyping quantum software applications. By 2025, the company expects to introduce such applications in machine learning, optimization problems, the natural sciences, and beyond.

Researchers hope ultimately to use quantum error correction to compensate for the mistakes quantum processors are prone to make. These schemes spread quantum data across redundant qubits, requiring multiple physical qubits for each single useful logical qubit. Instead, IBM plans to incorporate error-mitigation schemes into its platform starting in 2024, to prevent these mistakes in the first place. But even if wrangling errors ends up demanding many more qubits, IBM should be in a good position with the likes of its 1,121-qubit Condor. ■

AI REGULATIONS ARE COMING

Regulation is set to ramp up on the use of artificial intelligence online, as the European Parliament and Council's Digital Services Act went into effect at the end of 2022. The bill requires the largest platforms to implement antidisinformation measures and protect against discriminatory targeted advertising. Perhaps most important, it requires transparency in the algorithms used to provide product and content recommendations. This is likely a precursor to the E.U.'s larger AI Act, which is currently grinding through the legislative gears.



CARL DE TORRES/IBM

Icon illustration by Greg Mably

Galvani's system includes a nerve stimulator that attaches to the splenic nerve.

Arthritis Gets a Jolt

2023 will see the results of nerve stimulation for autoimmune disorders

By ELIE DOLGIN

Monique Robroek once had such crippling arthritis that even with the best available medications, she struggled to walk across a room. But thanks to an electronic implant fitted under her skin, she managed to wean herself off all her drugs and live pain-free for nearly a decade—until recently, when a viral illness made her rheumatoid arthritis (RA) flare up again.

Robroek's long remission is "very impressive" and rare among patients with RA, says her doctor Frieda Koopman, a rheumatologist at Amsterdam UMC, in the Netherlands. Robroek's experience highlights the immense potential of so-called bioelectronic medicine, also known as electroceuticals, an emerging field of treatment for diseases that have traditionally been managed with pharmaceuticals alone.

Robroek is also an outlier, though. Koopman led a landmark 17-person trial that tested whether modulating the nervous system's electrical-signaling patterns could tamp down inflammation and joint pain in RA. Robroek was one of only a handful who achieved appreciable and sustained reductions in disease severity, according to the 2016 paper.

Pilot studies like Koopman's are one thing, but scientific certainty demands randomized, sham-controlled trials. Doctors, neuroscientists, and bioengineers should soon get a better sense of the performance of electroceutical devices. In late 2023, SetPoint Medical, the Valencia, Calif., company that sponsored Koopman's initial trial, will report preliminary findings from Reset-RA, the first large-scale examination of nerve stimulation for an autoimmune condition. Like the earlier trial, the Reset-RA study targets the vagus nerve, the main conduit of brain–body communication, in an attempt to fight inflammation.

Expectations are charged. Although devices that harness electrical impulses are already widespread in medicine, these platforms all tap into neural circuits that directly impact diseased tissues; for example, deep-brain stimulators help with symptoms of Parkinson's disease by hacking the brain's motor-control center. None take aim at what Kevin Tracey, in an influential 2002 article, termed the "inflammatory reflex," a neural network that indirectly regulates immune responses to infection and injury through the vagus nerve and its connected organs.

Tracey, a former neurosurgeon who leads the Feinstein Institute for Medical Research in Manhasset, N.Y., was the first to show that vagus-nerve stimulation in rats could suppress the release of immune-signaling molecules. He later linked the effect to vagus-nerve signals running into the spleen, a fist-size organ in the abdomen where immune cells are activated. In 2007, Tracey cofounded SetPoint to bring the treatment to the clinic.

The company first repurposed an off-the-shelf implant used to control seizures in people with epilepsy. SetPoint optimized the stimulation parameters, using rodent studies for guidance, before giving the devices to patients like Robroek. She and the other recipients each had a cookie-size pulse generator surgically placed inside their chests. A wire snaked up the left side of the neck, where an electrode wrapped around the vagus nerve. It gave a gentle, 1-minute buzz of stimulation up to four times every day.

Paul Peter Tak, an immunologist and biotech entrepreneur who led the trial with Koopman, was worried that patients with RA might not want to undergo surgery and have hardware implanted under their skin. But after publicizing the study on Dutch television, Tak was inundated

GALVANI BIOELECTRONICS

with requests from patients who were sick of endless regimens of pills and injections. "This was my unplanned market research," Tak says. "To my surprise, there are many patients who might prefer a one-and-done surgery."

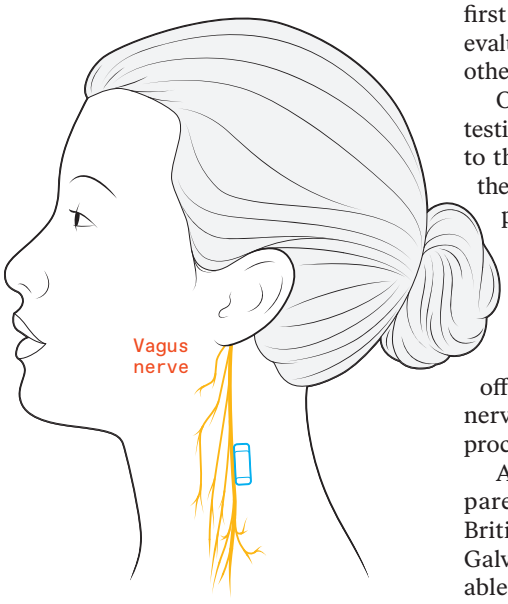
While the study's results were promising, the device itself was cumbersome. So SetPoint overhauled the platform, shrinking it down to a peanut-size neurostimulator with integrated electrodes and a wirelessly rechargeable battery, all encased inside a silicone holding pod that sits directly atop the vagus nerve in the neck. "It's like going from an old car to a Tesla—it's completely redesigned," says SetPoint's chief medical officer, David Chernoff.

A small trial performed in 2018 demonstrated that this miniaturized device was safe. The 250-person Reset-RA study, in which half the participants receive no stimulation for the first 12 weeks after implantation, is now evaluating efficacy. If it works, trials for other autoimmune diseases could follow.

Other companies, meanwhile, are testing devices that target nerves closer to the site of immune activation—"at the business end," says Kristoffer Famm, president of the British company Galvani Bioelectronics. This end-organ approach to nerve zapping, argues Famm, should allow for more precise, disease-specific neuromodulation, without the off-target effects of shocking the vagus nerve, which is central to many bodily processes.

A joint venture between Google's parent company, Alphabet, and the British pharmaceutical company GSK, Galvani is now evaluating its implantable splenic-nerve stimulator in small numbers of patients with RA. Another company called SecondWave Systems, headquartered in Minneapolis, is also testing whether spleen-directed ultrasound waves can offer the same immune-quelling effects without the burden of invasive surgery. Both Galvani and SecondWave expect to announce first-in-human data within the next year.

"Neuromodulation is definitely having a moment," says Gene Civillico, a neurotechnologist at Northeastern University, in Boston, who previously oversaw bioelectronics research efforts at the U.S. National Institutes of Health. "Controlling nervous tissue in a spatially and temporally precise way is going to be the way that we cure or modify a lot of disease states," Civillico contends. In the coming year, SetPoint and other companies hope to prove him right. ■



The vagus nerve travels down from the brain through the neck [top] to innervate the spleen and other vital organs. SetPoint shrank its nerve stimulator [bottom] so that it can be implanted in a patient's neck instead of the chest.

TOP: CHRIS PHILPOT; BOTTOM: SETPOINT MEDICAL

PRIZEFIGHT FOR RAIN-FOREST TECH

In early 2023, Singapore will welcome 15 teams to the jungle for the semifinals of the XPrize Rainforest competition. The semifinalists, hailing from all over the world, will show off their biodiversity-testing tech in the hopes of making the cut to the finals, set for 2024. Judges will be looking for "a process for improving autonomous operations, new detection methodologies, and methods for rapid data integration that provide unprecedented levels of detail in real time." The competition kicked off in 2019, and XPrize's net investment is US $10 million. XPrize is hoping that the incentive and competitive spirit will help save the rain forests.

Icon illustration by Greg Mably

Exascale Comes to Europe

Germany will host JUPITER, Europe's entry into the realm of exascale supercomputing

By MICHAEL DUMIAK

Frontier, the world's first exascale supercomputer—or at least the first one that's been made public—is coming on line soon for general scientific use at Oak Ridge National Laboratory in Tennessee. Another such machine, Aurora, is seemingly on track to be completed any day at Argonne National Laboratory in Illinois. Now Europe's getting up to speed. Through a €500 million pan-European effort, an exascale supercomputer called JUPITER (Joint Undertaking Pioneer for Innovative and Transformative Exascale Research) will be installed sometime in 2023 at the Forschungszentrum Jülich, in Germany.

Thomas Lippert, director of the Jülich Supercomputing Center, likens the addition of JUPITER, and the expanding supercomputing infrastructure in Europe more broadly, to the construction of an astonishing new telescope. "We will resolve the world much better," he says. The European Union–backed high-performance computing arm, EuroHPC JU, is underwriting half the cost of the new exascale machine. The rest comes from German federal and state sources.

Exascale supercomputers can, by definition, surpass an exaflop—more than a quintillion floating-point operations per second. Doing so requires enormous machines. JUPITER will reside in a cavernous new building housing several shipping-container-size water-cooled enclosures. Each of these enclosures will hold a collection of closet-size racks, and each rack will support many individual processing nodes.

How many nodes will there be? The numbers for JUPITER aren't yet set, but you can get some idea from JUWELS (shorthand for Jülich Wizard for European Leadership Science), a recently upgraded system currently ranking 12th on the Top500 list of the world's most powerful supercomputers. JUPITER will sit close by but in a separate building from JUWELS, which boasts more than 3,500 computing nodes all told.

With contracts still out for bid at press time, scientists at the center were keeping *schtum* on the chip specs for the new machine. Even so, the overall architecture is established, and outsiders can get some hints about what to expect by look-

SASCHA KREKLAU/FORSCHUNGSZENTRUM JÜLICH

The existing supercomputing resources at the Forschungszentrum Jülich, shown here, will soon be augmented by JUPITER, Europe's first exascale supercomputer.

ing at the other brawny machines at Jülich and elsewhere in Europe.

JUPITER will rely on GPU-based accelerators alongside a universal cluster module, which will contain CPUs. The planned architecture also includes high-capacity disk and flash storage, along with dedicated backup units and tape systems for archival data storage.

The JUWELS supercomputer uses Atos BullSequana X hardware, with AMD EPYC processors and Mellanox HDR InfiniBand interconnects. The most recent EuroHPC-backed supercomputer to come online, Finland-based LUMI (short for Large Unified Modern Infrastructure) uses HPE Cray hardware, AMD EPYC processors, and HPE Slingshot interconnects. LUMI is currently ranked third in the world. If Jupiter follows suit, it may be similar in many respects to Frontier, which hit exascale in May 2022, also using Cray hardware with AMD processors.

"The computing industry looks at these numbers to measure progress, like a very ambitious goal: flying to the moon," says Christian Plessl, a computer scientist at Paderborn University, in Germany. "The hardware side is just one aspect. Another is, How do you make good use of these machines?"

Plessl has teamed up with chemist Thomas Kühne to run atomic-level simulations of both HIV and the spike protein of SARS-CoV2, the virus that causes COVID-19. Last May, the duo ran exaflop-scale calculations for their SARS simulation—involving millions of atoms vibrating on a femtosecond timescale—with quantum-chemistry software running on the Perlmutter supercomputer. They exceeded an exaflop because these calculations were done at lower resolutions, of 16 and 32 bits, as opposed to the 64-bit resolution that is the current standard for counting flops.

Kühne is excited by JUPITER and its potential for running even more demanding high-throughput calculations, the kind of calculations that might show how to use sunlight to split water into hydrogen and oxygen for clean-energy applications. Jose M. Cela at the Barcelona Supercomputing Center says that exascale capabilities are essential for certain combustion simulations, for really-large-scale fluid dynamics, and for planetary simulations that encompass whole climates.

Lippert looks forward to a kind of federated supercomputing, where the several European supercomputer centers will use their huge machines in concert, distributing calculations to the appropriate supercomputers via a service hub. Cela says communication speeds between centers aren't fast enough yet to manage this for some problems—a gas-turbine combustion simulation, for example, must be done inside a single machine. But this approach could be useful for certain problems in the life sciences, such as in genetic and protein analysis. The EuroHPC JU's Daniel Opalka says European businesses will also make use of this burgeoning supercomputing infrastructure.

5 million

Number of modern laptop computers needed to approach JUPITER's raw processing power

Even as supercomputers get faster and larger, they must work harder to be more energy efficient. That's especially important in Europe, which is enduring what may be a long, costly energy crisis.

JUPITER will draw 15 megawatts of power during operation. Plans call for it to run on clean energy. With wind turbines getting bigger and better, JUPITER's energy demands could perhaps be met with just a couple of mammoth turbines. And with cooling water circulating among the mighty computing boxes, the hot water that results could be used to heat homes and businesses nearby, as is being done with LUMI in Finland. It's one more way this computing powerhouse will be tailored to the EU's energy realities. ■

UNITED STATES' WIND ON THE WIRE

The largest renewable-energy infrastructure project in U.S. history—an $8 billion wind farm and transmission line—is set to begin construction in 2023. San Francisco-based Pattern Energy took over the projects, called SunZia Wind and SunZia Transmission, from Southwestern Power Group in July 2022. The wind part of the project consists of a total of 3,000 megawatts from wind farms to be built in three counties in New Mexico. An 885-kilometer bidirectional high-voltage direct-current transmission line will run from New Mexico and south-central Arizona. The transmission line will sidestep the growing difficulties of connecting renewable-energy sources to the power grid.

Illustration by Greg Mably

No More "No Service"

Cellphones will increasingly text via satellite

BY LUCAS LAURSEN

Illustration by MCKIBILLO

In 2023, you or someone you know will be able to send a text message through space. Late in 2022, hardware behemoths Huawei and Apple released cellular telephones capable of texting on traditional satellite-communications networks. A pair of ambitious startups, AST SpaceMobile and Lynk Global, also started building new low Earth orbit (LEO) satellite networks designed to reach conventional 5G cellphones outside their coverage areas.

"Offering direct satellite access to smartphones without modifications would allow access to billions of devices worldwide," says Symeon Chatzinotas, the head of the University of Luxembourg's SigCom research group.

Users looking to connect via satellite won't need the bulky, expensive commercial satphones that have been available since the late 1990s—but they also won't have conventional calling or high-bandwidth data streaming just yet. Satellite connections are still plenty useful, though. To begin with, people could use texting to signal for help if need be, no matter where they are, as long as they have a clear view of the sky. That is, their mobile phones will have capabilities similar to existing pocket devices like Garmin's inReach communicator.

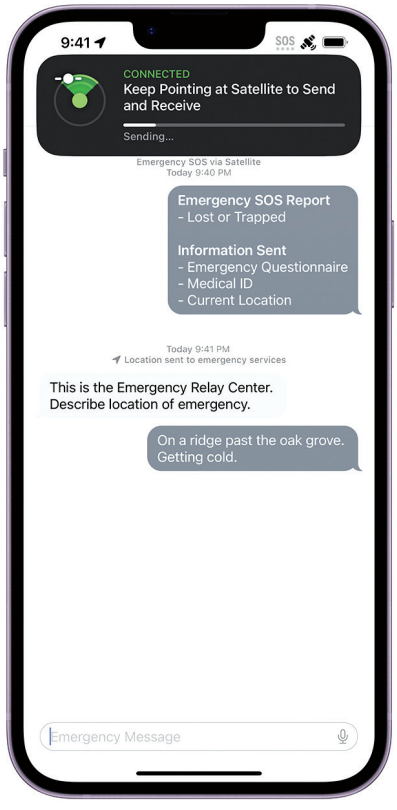
Huawei has not said when its service will begin working, but Apple's partnership with Globalstar, dubbed Emergency SOS via satellite, has been operational since November 2022. As of this writing, Lynk Global has agreements with 23 telecom providers to begin commercial operations in 2023. AST SpaceMobile says it plans to launch its first five commercial satellites late in 2023, has agreements or understandings with more than 25 telecom providers around the world, and should begin commercial operations in 2024.

Splashy announcements of satel-

This rendering of AST SpaceMobile's BlueWalker 3 test satellite, launched on 10 September 2022, shows the satellite's appearance with its antennas fully deployed. The antennas' surface area—64 square meters—enables the satellite to function as a long-distance cell tower for phones on Earth's surface.

AST SPACEMOBILE

An AST SpaceMobile employee [right] sets up a test unit of the BlueWalker 3 satellite's modular antenna array; the final array includes 148 such units. This mock-up [below] shows the app for Apple's Emergency SOS via satellite, which enables emergency texting in areas with no terrestrial coverage.



lite-cellular connectivity from Apple, Starlink, and T-Mobile in the third quarter of 2022 promoted the idea of anywhere, any-kind connectivity. The first services won't be that slick, though. Apple and Huawei will both connect initially to older satellites in higher orbits, for which it could take more than 10 minutes to establish a connection. Even the newer LEO networks, such as Lynk Global's, currently advertise satellite texting but are not yet promising the higher-capacity link that a voice or video call would require.

AST SpaceMobile says that as the company adds satellites, it will be up to its mobile-network-operator (MNO) partners to decide whether to market the bandwidth in small increments to many users for texting or voice-only calls or to offer data-heavy services to select users. Lynk doesn't mind its competitors' aspirational advertising campaigns, says Lynk Global CEO Charles Miller: "They educated the market. It's only going to make people want more."

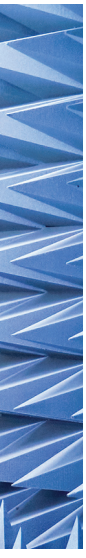
These new offerings are possible thanks to a handful of advances that are now maturing. Advances include the declining cost of satellite manufacturing and the shrinking size of satellites themselves, making it affordable to build many more satellites than in the past. And with many more of them, it's possible to put the satellites into lower orbits, between 300 to 600 kilometers above Earth, where each covers less ground.

OUT WITH RED TAPE, IN WITH THE FIBER

Germany aims to triple the amount of fiber cable installed by the end of 2025, in an effort called *Gigabitstrategie*. One of the strategies the German government will use to accomplish this ambitious goal is to clear some of the red tape around fiber projects by the end of 2022. It plans to centralize the project-approval process, currently seen as a municipality-dependent bureaucratic nightmare, clearing the way for a massive ramp-up in construction in early 2023. The government also plans to use the innovative microtrenching technique to lay down fiber in narrow 5-centimeter-wide channels dug by the side of the road without interrupting traffic.

LEFT: APPLE; RIGHT: AST SPACEMOBILE

Illustrations by Greg Mably



	AST SpaceMobile	Lynk Global
Satellites deployed by end of 2023	5 Block 1 BlueBirds	12 satellites
Planned constellation size	Approximately 170 satellites	5,110 satellites
Orbital height of constellation	550 to 700 kilometers	500 km
Constellation completion date	First commercial service in 2024	2027
Size of individual satellites	Block 1 BlueBirds: 64-square-meter antennas Block 2 BlueBirds: 128-m^2 antennas	First generation: 1-m^2 satellites Second generation: 4-m^2 satellites

But closer satellites allow handsets with less power to reach them.

Another improvement is in software-defined radios—chips that can transmit and receive on different wavelengths modulated by software running aboard the satellite. In the past, sending and receiving such a wide range of different wavelengths required distinct hardware. Digital signal processing enables these chips to do the work of a complicated array of hardware. "Software-defined radio means the phased-array antennas can do frequency hopping as we switch from country to country," Miller says. That technology makes it viable to pack more antenna capability into less space—Lynk will start with relatively small 1-square-meter antennas, but it plans to install bigger, more effective ones on its satellites in the future.

500–700 km

The distance between a LEO satellite and a cellphone, compared with less than a kilometer for a terrestrial cell tower

AST SpaceMobile chief strategy officer Scott Wisniewski says larger antennas are a big part of AST's strategy: "We think that's very important to communicate with low-power, low-signal-strength phones." AST plans to deploy antennas up to around 400 m^2, which would be the largest commercial telecom arrays in LEO.

Even so, having phones communicate with satellites rather than cell towers is tricky because of the much larger signal delays. "Everything about a phone is built around time-synching on the order of 5 to 10 milliseconds," Wisniewski says. "That works just fine with a tower that's a quarter mile away, 3 miles away even, but not for orbit." AST is developing hardware solutions with Nokia and Rakuten that tell the core network how to wait longer for satellite signals.

In 2023, Apple and Huawei will be testing how much use they can get from older communications satellites through their flagship handsets, equipped with new chips. Meanwhile, if things go according to Lynk Global's plan, by spring of 2023 the company will be offering commercial service to its MNO partners. AST may have its first commercial satellites in space but would still be testing and configuring them.

Network operators "historically asked, 'How is this possible?'" Wisniewski says. "Lately it's more about 'How can we use this best, when can we use this, what's the best market strategy for each market?'" For people living in certain countries, 2023 could be the year when they are no longer troubled by the words "No Service." ■

REVENGE OF THE GEOSYNCHRONOUS SATELLITES!

Compared with Starlink's sky-cluttering swarms of tiny satellites, San Francisco-based Astranis's plans may seem old-school. It aims to launch a lone humdrum geostationary satellite. But this satellite is the first of a new breed, dubbed microGEO. It's about one-twentieth the size of the minibus-scale geostationary satellites already in orbit, allowing for cheap and quick deployment. This first microGEO will launch in early 2023 and start providing service to Alaska, tripling the state's satellite bandwidth while cutting its cost. That same year, the company plans to launch four more microGEOs. One will provide Internet to rural Peru, two will service airplanes and cruise liners, and the final satellite's use is yet to be disclosed.

A Cryptocurrency for the Masses or a Universal ID?

CONTINUED FROM P. 45

But the coin has yet to be released—those who sign up get an IOU, not actual cryptocurrency—and the company has released few details on how it will work. "They haven't shared anything regarding what their currency model or their economic model is going to be," says Anna Stone, who leads commercial strategy for a nonprofit called Good Dollar. "It's just not yet clear how individual users will benefit."

Good Dollar distributes small amounts of its own cryptocurrency to anyone who signs up, as a form of UBI. Stone says the project has focused on creating a sustainable stream of UBI for claimants, while Worldcoin seems to be committing far more resources to developing its PoP protocol than the currency itself. "Offering people free crypto is a powerful lead-generation tactic," she says. "But getting people into your system and getting people using your currency as a currency are two quite different challenges."

Leading UBI proponent Karl Widerquist, a professor of philosophy at Georgetown University–Qatar, says he's skeptical of the potential of cryptocurrencies for boosting financial inclusion or enabling UBI. He says their inherently volatile prices make them unsuitable as currency. But Worldcoin's one-time distribution seems even less likely to succeed, he says, because most people around the world are so poor that they spend everything they have right away. "The majority of people in the world are going to have none of this currency very quickly."

The company's vision for Worldcoin has also shifted as the importance of World ID has grown. While the company can't dictate what the token will be used for, Sven Seuken, Worldcoin's head of economics, says it is now positioning the coin as a governance token that gives users a stake in a blockchain-based type of entity called a decentralized autonomous organization (DAO). The company has ambitions to slowly transfer governance of its protocol to a DAO that's controlled by users, with voting rights linked to their Worldcoin holdings. Tokens would act less as a payment method and more like shares in a company that manages the World ID platform.

This pivot wasn't reflected in the pitch at the college in Bangalore, where enrollees were sold on the potential of a fast, cheap way to transfer money around the world. Seuken admits the company needs to update its public communications around the benefits of signing up, but he says explaining World ID's value at this stage of adoption is challenging.

Worldcoin's biggest challenge may not be the functionality of its technology, but questions of trust.

"Convincing users initially to sign up by pitching World ID, this would be a really hard sell," he says.

Informed consent is important, though, says Jon Callas, director of public-interest technology at the Electronic Frontier Foundation. It's problematic, he says, if users don't realize they're signing up for a global identity system, especially one that involves biometrics, which are a uniquely sensitive form of authentication. "It's really hard to revoke and reissue your iris," says Callas.

While ZKPs provide strong mathematical guarantees of privacy, implementation mistakes can leave gaps that attackers can exploit, says Martin Albrecht, a professor of information security at Royal Holloway, University of London. In 2020, researchers bypassed ZKPs that had been used to anonymize transactions in the privacy-focused cryptocurrency Zcash by exploiting their knowledge that the time taken to generate a proof correlated to the content of transaction data (specifically, the transaction amount).

Worldcoin's head of blockchain, Remco Bloemen, says that even if the company's ZKPs were cracked, there wouldn't be a leak of biometric information, as the ZPKs aren't connected to users' iris hashes and are based only on their private keys. But Albrecht says revealing a user's private key is still a significant problem as it would let you impersonate them. "Once you know someone's private key, it's game over," he says.

The most obvious security risk comes from the fact that enrollees are currently given the option to store their unhashed iris scans, a policy the company gave conflicting reasons for. Its website at one point explained that this data helps train its algorithms, a line repeated at the sign-up event. But Blania said the data is held to automatically recompute people's iris hashes when the company's models are updated. He couldn't say when these models would be finalized and the company would no longer need the data.

The sensitivity of Worldcoin's biometric data is debatable. No other personal information is collected at registration, says Worldcoin's Sada, so there's nothing connecting users to their scans. Even if you could match the scans taken by Worldcoin to iris scans collected elsewhere, little would be revealed. "The most you could learn from that set of iris codes is that I participated in Worldcoin," he says.

Glen Weyl, an economist at Microsoft Research, says that worries about Worldcoin's threats to privacy are overblown, given that the biometrics aren't linked to anything. But Worldcoin's stringent privacy protections have introduced a critical weakness, he adds. Because biometric authentication is a one-time process, there is no ongoing link between users and their World IDs. "You've just found a way to generate a key, and that key can be sold or disposed of in any way people want," he says. "They have no framework, in any sense, for making sure these wallets are tied to the people who received them, other than their trust relationship with the people that they've hired to do the recruiting."

Without an ongoing link between World ID and the underlying biometrics, it's impossible to audit the registry of users, says Santiago Siri, board member of a competing digital-identity system

called Proof of Humanity (PoH). That's why PoH has built its registry of unique humans by getting people to upload videos of themselves that others can challenge if the videos seem fake. Siri concedes that the approach is hard to scale and has significant privacy challenges, but he says the ability to audit a system is critical for its trustworthiness. "How can I verify that of those 750,000 [Worldcoin] identities, 700,000 are not fake, or controlled by Andreessen Horowitz?" he says. "No one will be able to verify that, not even the Worldcoin people."

It's also questionable how useful the concept of "unique humanness" really is outside of niche cryptocentric applications, says Kaliya Young, an identity researcher and activist. Identity plays a broader role in everyday life, she says: "I care what your university degrees are, where you were born, how much money you make, all sorts of attributes that PoP doesn't solve for."

Worldcoin's biggest challenge may not be the functionality of its technology but questions of trust. The central goal of blockchains is to avoid relying on centralized authorities, but by using complex, custom hardware to recruit users, the company is setting itself up as a powerful arbiter of digital identity. "Worldcoin posits that everyone in the world should have their eyeball scanned by them and they should be the decider of who's a unique human," says Young. "Please explain to me how that's not ultracentralized."

What's more, Microsoft's Weyl says, the company's reliance on the "creepy all-seeing eye" of the Orb may create problematic associations. According to Weyl, projects like Worldcoin may give people "a sense of a dystopian future" rather than one that is "hopeful and inclusive."

In the end, the success of Worldcoin's ambitious 2023 goals may boil down to a question of narrative. The company is peddling a message of financial inclusion and wealth distribution while critics raise concerns around privacy and transparency. It remains to be seen whether the world will truly buy into Worldcoin. ■

Finally, an eVTOL You Can Buy Soonish

CONTINUED FROM P. 35

There are early tech adopters and also people who are already aviators and are "passionate about the future of electric flight, who love the idea of being able to have their own personal vertical-takeoff-and-landing, low-maintenance, clean aircraft that they can fly in rural and uncongested areas," Karklin says. "One of them is a business owner. He has a plant that's a 22-mile drive but would only be a 14-mile flight, and he wants to install charging infrastructure on either end and wants to use it to commute every day. We love that."

Others are less certain about how, or even whether, this market segment will establish itself. "When it comes to personal-use eVTOLs, we are really struggling to see the business case," says Sergio Cecutta, founder and partner at SMG Consulting, where he studies eVTOLs among other high-tech transportation topics. "I'm not saying they won't sell. It's how many will they sell?" He notes that Opener is not the only eVTOL maker pursuing a path to success through the ultralight or some other specialized FAA category. As of early November, the list included Alauda Aeronautics, Air, Alef, Bellwether Industries, Icon Aircraft, Jetson, Lift Aircraft, and Ryse Aero Technologies.

What makes Opener special? Both Karklin and Leng emphasize the value of all that surrounds the BlackFly aircraft. For example, there are virtual-reality-based simulators that they say enable them to fully train an operator in 10 to 15 hours. The aircraft themselves are heavily instrumented: "Every flight, literally, there's over 1,000 parameters that are recorded, some of them at 1,000 hertz, some 100 Hz, 10 Hz, and 1 Hz," says Leng. "All that information is stored on the aircraft and downloaded to our database at the end of the flight. When we go and make a software change, we can do what's called regression testing by running that software using all the data from our previous flights. And we can compare the outputs against what the outputs were during any specific flight and can automatically confirm that the changes that we've made are without any issues. And we can also compare, to see if they make an improvement."

Ed Lu, a former NASA astronaut and executive at Google, sits on Opener's safety-review board. He says what impressed him most when he first met the BlackFly team was "the fact that they had based their entire development around testing. They had a wealth of flight data from flying this vehicle in a drone mode, an unmanned mode." Having all that data was key. "They could make their decisions based not on analysis, but after real-world operations," Lu says, adding that he is particularly impressed by Opener's ability to manage all the flight data. "It allows them to keep track of every aircraft, what sensors are in which aircraft, which versions of code, all the way down to the flights, to what happened in each flight, to videos of what's happening." Lu thinks this will be a huge advantage once the aircraft is released into the "real" world.

Karklin declines to comment on whether an ultralight approval, which is governed by what the FAA designates "Part 103," might be an opening move toward an FAA type certification in the future. "This is step one for us, and we are going to be very, very focused on personal air vehicles for recreational and fun purposes for the foreseeable future," he says. "But we've also got a working technology stack here and an aircraft architecture that has considerable utility beyond the realm of Part-103 [ultralight] aircraft, both for crewed and uncrewed applications." Asked what his immediate goals are, Karklin responds without hesitating. "We will be the first eVTOL company, we believe, in serial production, with a small but steadily growing revenue and order book, and with a growing installed base of cloud-connected aircraft that with every flight push all the telemetry, all the flight behavior, all the component behavior, all the operator-behavior data representing all of this up to the cloud, to be ingested by our back office, and processed. And that provides us a lot of opportunity." ■

Jobs: School of Integrated Circuits at Sun Yat-sen University is Recruiting Faculty Worldwide

Sun Yat-sen University, founded by Dr. Sun Yat-sen, has an educational tradition spanning over 100 years. Under the direct supervision of the Ministry of Education of the People's Republic of China, and strongly supported by both the Ministry and Guangdong Province, Sun Yat-sen University has developed into a modern comprehensive university that enjoys a reputation as a top-tier university nationally and a renowned university internationally. With five campuses in the three cities of Guangzhou, Zhuhai and Shenzhen, and ten affiliated hospitals, the University is striving to become a world-class university and global center of learning.

The School of Integrated Circuits at Sun Yat-sen University is now open to the world for faculty recruitment. Highly-qualified and motivated academic researchers from across the world are sincerely invited to join us! Our goal is to build world-class team of academics and to foster the academic excellence of the students.

The School of Integrated Circuits at Sun Yat-sen University (hereinafter referred to as "the school") was established in February 2021. It is one of the first schools of integrated circuits in China, founded in response to the effort by the State Council and the Ministry of Education to construct " Science and Engineering of Integrated Circuits " as a first-level discipline and add it to the discipline system of higher education. As a benchmark school/department in Guangdong-Hong Kong-Macao Greater Bay Area, the school, aligning with the principle of " facing the forefront of the world's science and technology, the main economic battlefield, the major needs of the country, and the people's lives and health ", serves the major demands of the nation for high-performance general integrated circuits and high-end application-specific IC chips. The school endeavors to build a new engineering discipline system for the microelectronic industry, and construct the top-tier IC learning and research institute of China.

1 Faculty positions:
The School of Integrated Circuits consists of two distinctive divisions: science and engineering of integrated circuits, and electronic science and technology. The school deals with the key links in the IC industry chain, such as design and simulation, manufacturing process, packaging testing, equipment materials, design tools and industrial applications.

2 Position description and requirements:
Positions:
"100 Top Talents Plan"
We are looking for researchers in the following classes who:

Class-I: leading talents and top researchers
1) have engaged in promising research work involving critical general technologies with major innovations, and made landmark achievements with significant impact;
2) have important worldwide influence, and equivalent academic status and academic level, or has outstanding academic achievements in corresponding disciplines;
3) are generally preferred to be 50 years of age or under.

Class-II: Young or middle-aged outstanding talents
1) have distinguished research potential and technological innovation potential;
2) have important innovation prospects in research direction, and have obtained professional achievements and scientific research achievements recognized at home and abroad;
3) are generally preferred to be 40 years of age or under.

Class-III: Young top-notch researchers
1) have significant ability to think and conduct research innovatively, and have demonstrated outstanding development potential;
2) have high-level and innovative professional achievements;
3) are generally preferred to be 35 years of age or under.

Class-IV: Young talents
1) have good educational and scientific research background, and have demonstrated active and innovative thinking ability and impressive development potential;
2) have the final academic degree completed and the certificate granted within the last three years;
3) are generally preferred to be 35 years of age or under.

3 Work location:
Shenzhen Campus
Shenzhen Campus of SYSU, one of the five main campuses of the University, is located in Guangming District, Shenzhen, covering an area of about 3.143 square kilometers with a building area of about 2.3 million square meters.

4 Salaries and benefits:
We provide
1. Competitive salary and campus subsidies.
2. Sufficient and comfortable work and living environment: The university provides sufficient and proper space to ensure everyday work and life comfort; On-campus apartments are available for rental to employees.
3. Strong medical resources and educational support from the affiliated schools: 10 affiliated hospitals of Sun Yat sen University provide high-level medical care to employees; Affiliated primary and secondary schools in Guangzhou, Zhuhai and Shenzhen campuses promise high-quality educational resources for the children of teachers and staff.
4. Good school culture and talent service environment: the university provides first-class sports venues and facilities, and special school sports funds are established to help employees participate in their chosen sport.
5. High-level talents based on Shenzhen campus are eligible for rewards and subsidies granted by the Shenzhen municipal government.

5 Contact information:
If you want to join the School of Integrated Circuits at Sun Yat-sen University, please send your job intention, resume and representative academic achievements to the following email address. If you need more information, please contact us directly. We will wholeheartedly provide all-round services for your application.

email: jcdlxy@mail.sysu.edu.cn, Ms. Li
please entitle your email as follows in the subject line: position intended to apply + full name + final degree granting institution + major or division
Tel: +86-020-39921236

CASE WESTERN RESERVE UNIVERSITY
CASE SCHOOL OF ENGINEERING

Faculty Position in Electrical Engineering
Department of Electrical, Computer, and Systems Engineering
Case Western Reserve University, Cleveland, Ohio

The Department of Electrical, Computer, and Systems Engineering at Case Western Reserve University (CWRU) invites applications for a tenure-track faculty position in Electrical Engineering at the Assistant Professor level. Appointments will be considered for starting dates as early as July 1, 2023. Candidates must have a Ph.D. degree in Electrical Engineering or a related field.
The faculty search is focused on the broader area of robotics. The department is particularly interested in candidates in the field of robotics whose focus is in, or at the intersection of, robot perception, machine vision, machine learning, and robot autonomy. Candidates whose research has applicability to areas such as shared autonomy, human-in-the-loop systems, assistive robotics, or intelligent multimodal robotic perception and manipulation are highly desirable. Additional information about the position, department, and application package is available at **https://engineering.case.edu/ecse/employment**.
CWRU provides reasonable accommodations to applicants with disabilities. Applicants requiring a reasonable accommodation for any part of the application and hiring process should call 216-368-3066.

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The Min H. Kao Department of Electrical Engineering and Computer Science (EECS) within Tickle College of Engineering at The University of Tennessee - Knoxville (UTK) is seeking candidates for six (6) tenure-track faculty positions at the assistant or associate professor level in the areas of Computer Science or Computer Engineering. The targeted appointment date is August 1, 2023.

Application deadline is December 15, 2022. Applications received after the deadline *may* be considered until all positions are filled.

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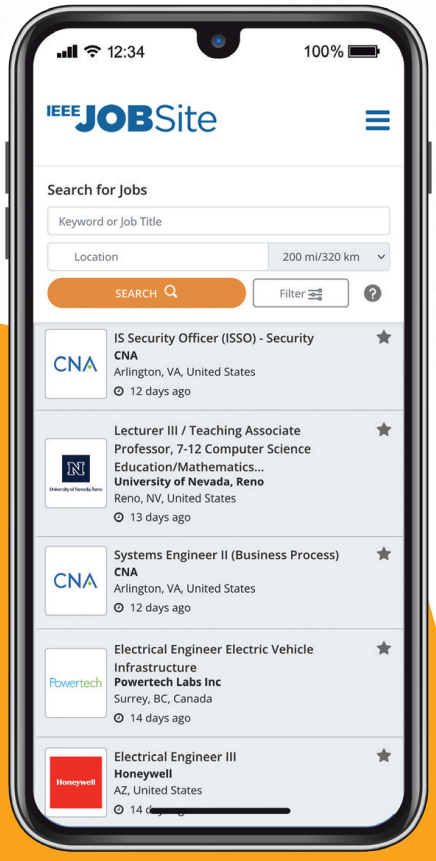

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UNIVERSITY OF CENTRAL FLORIDA

Assistant and Associate Professors in ECE

The Department of Electrical and Computer Engineering (ECE) at the University of Central Florida (UCF) invites applicants for the following faculty positions at the rank of assistant professor (tenure-earning) or associate professor (tenured) with a start date of August 2023.

Three (3) positions are open in the general area of semiconductors with particular focus on 1) wide bandgap and high-power devices and circuits, III-V and heterostructured devices and circuits, THz devices and circuits; 2) beyond-CMOS devices and systems (e.g., neuromorphic, topological, 2D, and spintronic); and 3) radiation-hardened devices, systems and technologies, harsh-environment sensors and systems, high-temperature devices and circuits, electronic devices and circuits resilient to single-event effects, and real-time systems (including robotic) with potential applications to space.

Two (2) positions are open in the general area of next generation computing with particular focus on 1) Digital physical design and CAD for VLSI, and/or deeply-scaled CMOS digital physical design, optimization, and layout/tapeout, and post-CMOS computing devices beyond the transistor; and 2) computing and cyber-physical systems and devices for space including FPGAs, reliable embedded computing systems, and computing systems enabling adaptive hardware and robotic systems.

Two (3) positions are open in the general area of energy systems with particular focus on 1) reliable distributed energy resources (DER) for grid integration with an emphasis on various failure modes and degradation mechanisms common to inverters, micro-inverters, and DC optimizers; 2) resilience of energy systems with an emphasis on multidisciplinary tools from nonlinear dynamics, network theory, optimization, and control to analyze interdependent energy systems to develop innovative metrics and methodologies for resilience enhancement; and 3) energy storage systems with an emphasis on battery storage technologies, renewable electrolysis, and energy storage analysis.

One (1) position is open in the general area of hardware security with particular focus on hardware/chipmaking supply chain security, physically unclonable function (PUF) devices, hardware trojan, logic locking, physical side channels, hardware side-channel attack prevention, memory protection, post-quantum encryption hardware, secure data path design, and threat mitigation circuits.

Finally, several positions are open in the general area of artificial intelligence (AI) with particular focus on application of AI in robotics, computer hardware, connected and automated vehicles, neuromorphic computing, and next-generation wireless communication systems.

The application links for all these positions are available at **https://www.ece.ucf.edu/faculty-search/** and the applications will be considered until positions are filled. The successful candidates are expected to conduct impactful research and educate students (both undergraduate and graduate) in aforementioned areas of research. Establishing strong ties with industrial partners, both local and national, is of special interest. If you have any questions regarding these positions, please email: facultysearch@ece.ucf.edu.

As an equal opportunity/affirmative action employer, UCF encourages all qualified applicants to apply, including women, veterans, individuals with disabilities, and members of traditionally underrepresented populations. UCF's Equal Opportunity Statement can be viewed at:

http//www.oie.ucf.edu/documents/PresidentsStatement.pdf.

As a Florida public university, UCF makes all application materials and selection procedures available to the public upon request.

THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

The George Washington University
Department of Electrical & Computer Engineering
Assistant Professor of Electrical & Computer Engineering – AI Hardware

The Department of Electrical and Computer Engineering (ECE) at the George Washington University (GWU) invites applications for a tenure-track appointment starting in Fall 2023 at the rank of Assistant Professor. We are seeking outstanding candidates in Artificial Intelligence (AI) Hardware.

Applicants with expertise in hardware design for machine learning including but not limited to deep learning architectures, hardware accelerators and neuromorphic processors will be considered. Successful applicant will have the opportunity to collaborate with active researchers with interests in computer architecture, high-performance computing and emerging processing technologies such as photonic chips, magnetic devices and quantum computing devices, with potential applications to areas such as autonomous systems, personalized medicine, and imaging.

Applicants must have an earned doctorate in Electrical Engineering and/or Computer Engineering, or an equivalent engineering discipline at time of appointment; must demonstrate a solid publication record; must have established or exhibit potential to establish a strong externally sponsored research program; and must be committed to excellence in teaching at both undergraduate and graduate levels. With one of the highest percentages of women engineering students, the School of Engineering and Applied Science is committed to increasing the diversity of its faculty and staff.

The ECE department has 18 full-time faculty including 5 IEEE Fellows, a PECASE awardee and a number of NSF CAREER Award recipients and enjoys a very robust sponsored research portfolio. The department is housed in our state-of-art 500,000 sq. ft. Science and Engineering Hall integrating advanced laboratory and instructional facilities.

For more information and to apply, visit **https://www.gwu.jobs/postings/97705**.

广东省智能科学与技术研究院
Guangdong Institute of Intelligence Science and Technology

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About us
Guangdong Institute of Intelligence Science and Technology is a public research institution. It's located in Guangdong-Macao In-Depth Cooperation Zone in Hengqin, next to Macao City. The institute is focused on interdisciplinary research in the field of cognitive science, artificial intelligence, brain-inspired chips and computing systems. We are currently recruiting researchers at full professor, associate professor, assistant professor and postdoc levels.

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5. Cloud computing and large-scale computing systems
6. Service and application of AI data centers

Qualifications
1. Doctorate degree in bio-medicine, neuroscience, electronics and computer engineering, mathematics, or related area.
2. Have research experience for the corresponding positions, demonstrated ability to conduct quality research, and training of graduate students.
3. Full professor position shall have experience showing excellent scientific leadership and management skills.

Applications
Send copies of application materials (including CV, list of publications, academic degree certificate, 2-3 expert reference names, and other supporting materials) to the e-mail address linqijiao@gdiist.cn (specify the subject of the email: job application + name). After pre-screening, an interview will be organized.

Salary and benefits
Salary will be commensurate with experience and academic accomplishments. Starting annual salary of full professor is at 950k-1.35MCNY (1USD≈7.28CNY), associate professor at 650-950kCNY, assistant professor and postdoc is at 450-750kCNY.

Applicants are encouraged to check out the details about our Institute:
http://gdiist.cn (Chinese); **http://gdiist.cn/en/about** (English)

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Past Forward

In 1975, when this Amana Radarange was introduced, U.S. sales of microwave ovens surpassed those of gas ovens for the first time.

The Microwave's Slow Burn

In 1947, an employee at Raytheon coined the name Radarange for the company's new commercial product: an oven that cooked food using microwaves. Intended for restaurants, the oven was about the size of a refrigerator. It would take a while for the idea of cooking with electromagnetic waves to catch on. In 1965, Raytheon acquired Amana Corp., a manufacturer of home appliances, to develop a compact version for the modern home kitchen. Two years later, the Radarange hit the market at US $495 (about $4,400 today)—definitely a higher-end appliance. By 1975, prices had come down, and U.S. sales of microwave ovens were outpacing those of conventional gas ovens, as consumers finally began buying in to the convenience of quick cooking. ■

FOR MORE ON THE HISTORY OF MICROWAVE OVENS, see spectrum.ieee.org/pastforward-jan2023

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