ingenia

SEPTEMBER 2024

ISSUE
100

CELEBRATING 25 YEARS OF INGENIA

ENGINEERS TAKE CENTRE STAGE
DRIVING IMPACT IN THE WORLD
RESHAPING OUR FUTURE

Royal Academy
of Engineering

www.ingenia.org.uk

Royal Academy of Engineering

Published by the Royal Academy of Engineering
Royal Academy of Engineering
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With thanks to
Andy Coulson (proofreader)

Ingenia online can be found at **www.ingenia.org.uk**

Design
The Design Unit www.thedesignunit.com

Print
Pensord www.pensord.co.uk

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Front cover
Some of the engineering innovations that have shaped the past 25 years
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ISSN 1472-9768

WELCOME

Welcome to the 100th issue of *Ingenia*! In the 25 years since *Ingenia* was first published in 1999, the world has changed significantly, and engineering has been at the forefront of many of those changes.

For this issue, we have been delighted to have Dr Shini Somara onboard as a guest editor. As a mechanical engineer, broadcaster and author, Shini has helped us to further draw out the fun and real-world impact of engineering. We also invited *Ingenia* contributors, past and present, to share their thoughts on future engineering and technology achievements, on page 8, and invite you to join the conversation.

On page 18 you can read how innovations in technology have brought ABBA to life on the stage, entertaining thousands of people in the process. You can also learn how startup Aeropowder is using feathers to create biodegradable insulating materials for packaging, helping keep your food deliveries cool, and how First Light Fusion was inspired by the pistol shrimp's shockwave-emitting claw to create fusion energy.

We bring you the story of how an industry–academia collaboration has digitised manufacturing processes to ensure Fairy washing up liquid stays free from contamination. And we have spoken to Dr Eben Upton CBE FREng, Co-Founder of the Raspberry Pi, about how the credit-card-sized computer has changed the face of computing in the UK. Do also visit our website to find out how engineer Chris Bellamy is taking inspiration from naturing and designing items such as chairs, bandages and fabrics from living materials.

We look forward to continuing to tell the story of engineering over the next 25 years. We'd also love to hear your thoughts – what do you think might be the greatest future achievements in engineering innovation? Please let us know by emailing ingenia@raeng.org.uk or using #IngeniaMag on X.

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

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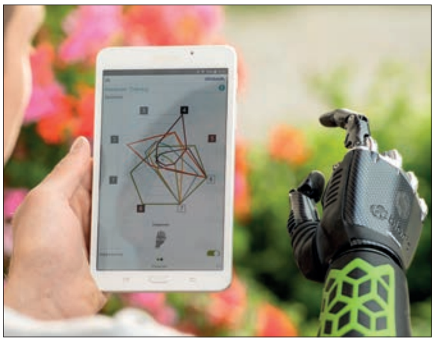


EDITORIAL

SOCIAL SUSTAINABILITY IN ENGINEERING

Dr Shini Somara, Guest Editor

I'm delighted to be guest editing the 100th edition of *Ingenia*. This issue marks the 25th year that the magazine has existed and like the industry, it has gone through some changes. Our desire for faster, taller and greater has been superseded by the urgent need for kinder, more considerate and steadfast solutions. Extreme environmental events remind us that our world is in flux and that engineers have the skills to safeguard us against vulnerability. It certainly has been an unprecedented quarter of a century and *Ingenia* has proudly documented its highlights.

Despite the external fluxes, engineering has continued to be the cornerstone of innovation and progress. From resilient infrastructure, sustainable approaches and reusable solutions, engineering has become more conscious as an industry, but there is still a long way to go. The pivotal role engineers play in shaping our future is only becoming more crucial. I have been particularly enthusiastic and inspired by the ambitions of the Royal Academy of Engineering (and hence *Ingenia*) in celebrating and embracing the principles of widening participation, equality, diversity, and inclusion (EDI). This, I hope, will be the underpinning of the next 25 years ahead.

On pages 4 and 5, esteemed past and present editors of *Ingenia* discuss a positive vision for its future. I share their renewed goal of inspiring and welcoming a wider demographic into engineering. Historically, engineering has earned itself a reputation of being an exclusive domain, dominated by one gender. This lack of diversity and inclusion limited the industry's talent pool, but also restricted the breadth of perspectives that drive innovation. The Royal Academy of Engineering has been committed to changing this, to recognise that a diverse and inclusive engineering workforce is a strategic necessity for global success – and acknowledge that engineering teams comprising individuals from varied backgrounds are better equipped to solve complex problems and generate novel solutions. There is no doubt that diversity enhances the relevance and applicability of outcomes to a broader segment of society and *Ingenia* has documented this well.

Personally, I have witnessed and experienced an evolving industry over the past two decades: one that is becoming more diverse and inclusive than ever before. But change takes time, and where I have hope and excitement is in the ambition to make engineering in the UK more accessible. Communication is key to this goal. Current and future engineers are upskilling themselves in communicating their craft and expertise, allowing us all to see how rich the industry is with creativity, ingenuity, expertise, and care for best practice. It is with these intentions that we will develop future innovations and solutions to our future and *Ingenia* will be at the forefront telling you all about it!

Over the years, *Ingenia* has increased its coverage of widening participation, showcasing engineers and engineering that have originated from unconventional backgrounds. Going forward, upskilling individuals who have not followed the well-trodden paths of university degrees into engineering careers creates a more interesting workforce. Apprenticeships and T levels are a fantastic pathway into engineering, bridging the divide between academia and industry, so everyone gains. The inclusion of a diverse range of socio-economic status, gender, ethnicity, disability, and geography provides opportunity through unity.

And we all play a part. Making the most of the wealth of untapped potential available is a collective endeavour that requires the engagement of educational institutions, industry, professional bodies, and individuals – all of whom are forming part of a growing *Ingenia* readership. *Ingenia* has evolved to serve an engineering profession and community that truly leaves no one behind, especially with its recent presence online. Hence, with the variety of pathways into engineering, equality, diversity and inclusion in engineering can be achieved and industry must take note. Securing future talent pools must begin now through supporting the education and development of our future engineers.

Sustainability became a buzzword approximately 50 years ago, sparking a wave of new thinking, practices and ambitions for recycling, re-purposing and reuse. Today we are starting to recognise that 'social sustainability' is crucial for the future of engineering too and achieved by creating working environments where individuals are celebrated for their abilities and contributions rather than judged on inherent biases. We all play a part in achieving this by ensuring that policies, practices, and cultures within educational institutions and workplaces are fair and nondiscriminatory. Moreover, providing equal access to professional development opportunities ensures that everyone has the chance to advance and excel in their careers.

This issue of *Ingenia* brings together a range of experiences, ideas, and viewpoints, fostering the creativity and innovation that exists in engineering throughout the past, present and future. The increased cultivation of diversity within our articles has been essential to valuing the contributions from a variety of engineers. Actively seeking underrepresented voices has been crucial for me as guest editor and I hope more of them feature in the future. Additionally, in celebrating diverse role models and their achievements in engineering I hope that we demonstrate that engineering is a sector where everyone can thrive, where hard work and commitment is valued and supported. Where differences are not only accepted but championed, so that individuals feel empowered to make a positive difference through their differences.

So, as we look to the next 25 years of engineering, I hope our articles highlight our commitment to widening participation. The engineering profession's potential is boundless when it harnesses the talents and perspectives of all individuals. So, let us build a strong engineering future together, so that it can be celebrated here at *Ingenia*, both in print and online in future issues to come.

BIOGRAPHY

Dr Shini Somara is a fluid dynamicist and media broadcaster. With a career spanning over two decades, Shini has significantly influenced the engineering landscape, particularly in inspiring young people and marginalised groups to pursue STEM careers. Her popular YouTube series, *Crash Course Engineering* and *Crash Course Physics*, have collectively garnered nearly 60 million views, making complex engineering concepts accessible and engaging to a global audience. Her book *Engineers Making a Difference*, distributed to 16,000 secondary schools in the UK, celebrates the diversity of the engineering profession. She continues to produce and host podcasts and other digital media content aimed at promoting underrepresented groups and women in STEM. Shini also currently serves as Pro Chancellor of Brunel University.

GET INVOLVED IN ENGINEERING

NEW SCIENTIST LIVE

Excel London and online
12 to 14 October

Across the weekend visitors can hear talks, get hands-on at interactive exhibitions and explore more about STEM. Ride a virtual reality rollercoaster, find out more about AI and learn about fusion energy. Monday's session is exclusively for schools groups. Book tickets at **live.newscientist.com**

INNOVATION INCOMING

Royal Academy of Engineering, London, and online
17 October

Join MacRobert Award winner Google DeepMind and an expert panel to hear about its GraphCast technology and its impact on weather forecasting and the intersection of AI and meteorology. It's free to attend, but please register online at **raeng.org.uk/events**

MANCHESTER SCIENCE FESTIVAL

Science and Industry Museum and venues across the city | 18 to 27 October

This 10-day festival of STEM includes events, immersive performances, family fun, and hands-on activities. Computer scientist, Dr Anne-Marie Imafidon, and the UK Space Agency's Head of Space Exploration, Libby Jackson, will also kick-start the festival with a guest-curated weekend of adult-only evening events. Find out more at **scienceandindustrymuseum.org.uk/manchester-science-festival**

REFRAMING *INGENIA* FOR THE NEXT GENERATION

As *Ingenia* marks its milestone 100th issue, former Editor-in-Chief Scott Steedman, current Editor-in-Chief Faith Wainwright, and Deputy Editor-in-Chief David Delpy got together to reflect on how the magazine has evolved over the past 25 years.

When *Ingenia* first launched in 1999, it began as a quarterly magazine aimed at opinion formers and Fellows of the Royal Academy of Engineering, to promote both Academy and engineering achievements. Its editorial policy aimed to reflect the economic and social importance of engineering, feature UK achievements and address political issues where possible. When Scott became Editor-in-Chief in 2004, he was tasked with overhauling it.

Scott: "I said I'd love to do it, but only if we can completely change the design. It was a great idea for the Academy to have a regular publication, but it wasn't clear who it was aimed at. The first issues were very interesting, quasi-academic, more like a technical journal, but what we really needed was a 'magazine'. I was very keen from the outset to make it accessible to a much wider readership and to reach a whole new audience."

David: "I'd always enjoyed it, but it was a very different journal back then."

Scott: "*Ingenia* had been set up by a number of very distinguished Fellows, including John Burland, Ian Nussey and Derek Hanson, and fortunately they were enthusiastic about the change. Our role wasn't to educate other engineers but to inspire people who don't know about engineering."

Since then, the magazine has increasingly targeted a nonexpert audience – reaching over 4,000 schools across the UK.

Faith: "It is important to improve public understanding of engineering – we've continued in the path that Scott set and redefined our primary audience as STEM-interested 13 to 25-year-olds. And beyond this, we aim to reach people who may influence these young people and those who may transition into engineering from another career as well."

David: "I think we are keen to give engineering more visibility in schools, which make up a large part of our audience."

Scott: "We had many teachers who were asking for multiple copies for students. In my view, the target audience isn't just young people already interested in engineering. Obviously, they should enjoy the magazine and reading about the projects, but it's the young people who are wondering about choosing engineering as a possible career, or who might be inspired further that I really wanted to reach. I liked the idea of inspiring and uplifting readers with real stories of engineering achievement, and always with a UK connection."

And those stories aim to celebrate the innovation in engineering and the engineers behind them.

Scott: "We've always asked, 'What's the challenge? Where's the engineering?' Engineering involves problem-solving, but we shouldn't waste space 'celebrating the problem'. For me, engineering is a way of thinking – what is the outcome? What are we trying to achieve? What's the impact? – rather than focusing on the technical solutions all the time."

Faith: "The way engineers think is at the heart of engineering, not the specific deliverable. It's what and how they practise. So, what you're saying there, Scott, I think is *Ingenia* is becoming much more how we think about engineering not so much about the problems. The articles showcase the imagination of engineers as they reach beyond the apparent problem and identify opportunities to create practical beneficial outcomes.

"Now, engineering is less talked about as a single discipline vocation. Rather, we bring out this aspect of shaping and looking at the world more

Scott Steedman

Faith Wainwright

David Delpy

holistically and looking at problems more as systems problems. One thing I'm really proud of with *Ingenia* is how we illustrate the diversity of engineering: different genres, walks of life, all sorts of different roles, from people who are creative writers talking about engineering to people who are leading in innovation, or specific project stories. Whatever somebody is interested in, I like to think every issue of *Ingenia* will have something for them."

Over the 25 years that *Ingenia* has been published, engineering has also changed.

David: "There have been many changes in engineering and in industry in general, and I think one thing that made a big change was when the United Nations set its Sustainable Development Goals [adopted by world leaders in September 2015 at an historic UN Summit], a lot of which are relevant to and depend upon engineering. And then in 2017, you had the National Academy for Engineering's Grand Challenges for Engineering, which more clearly set out long-term major engineering grand challenges. I think that these are things that have affected engineering from a policy rather than necessarily from an individual company point of view. Engineering has identified very long-term global grand challenges – things that it's going to have to focus on not just for five years, but possibly for generations!"

And *Ingenia* has tried to reflect that change.

David: "Originally, there was a real focus on all the stories being about UK engineering and UK companies, but the whole engineering landscape has changed. The young readers who are looking for jobs realise that jobs are not for life with one company. More jobs are with multinationals or with startups and it's now a very different environment."

Scott: "I think it's still important to have that UK connection in the magazine."

David: "Absolutely – we ought to be trying to push the UK aspects as much as possible, and most of the companies we talk to have some kind of link to the UK. I also think that now we are much more prepared to talk about research that is due to move out of the lab rather than just existing products."

Faith: "I think we've been very conscious, and this started under your tenure Scott, of really thinking about people: people influencing engineering, engineering for people, people who are doing the engineering. Our stories take you out of deep, technical journal-type thinking and try and bring out the impact for people."

Scott: "Yes, it's all about people, isn't it? And I feel as an engineer that I am trying to be an interface between society and what it needs. I try to communicate between the two. Engineers need to interpret the issues people are facing and bridge between the technical and nontechnical. And that goes for policy too."

Faith: "Yes, and when we think about how the world changes, the engineering influence on policymaking is vital."

As *Ingenia* looks to the future, we'll continue printing the magazine but will also be moving more online – reaching audiences through the monthly e-newsletter and revitalised website (www.ingenia.org.uk), which also hosts our archive.

Scott: "Over the years we have compiled an enormous amount of high-quality content. *Ingenia* should always focus on celebrating engineering, uplifting and enlightening as many people as possible about how you think, approach and solve challenges that result in practical outcomes. How the thinking evolves from the challenge to the achievement and the human stories in there that are so important to bring together the collaboration, the outcome, the shaping of the problem, and then the solution, with a little bit of the technical magic."

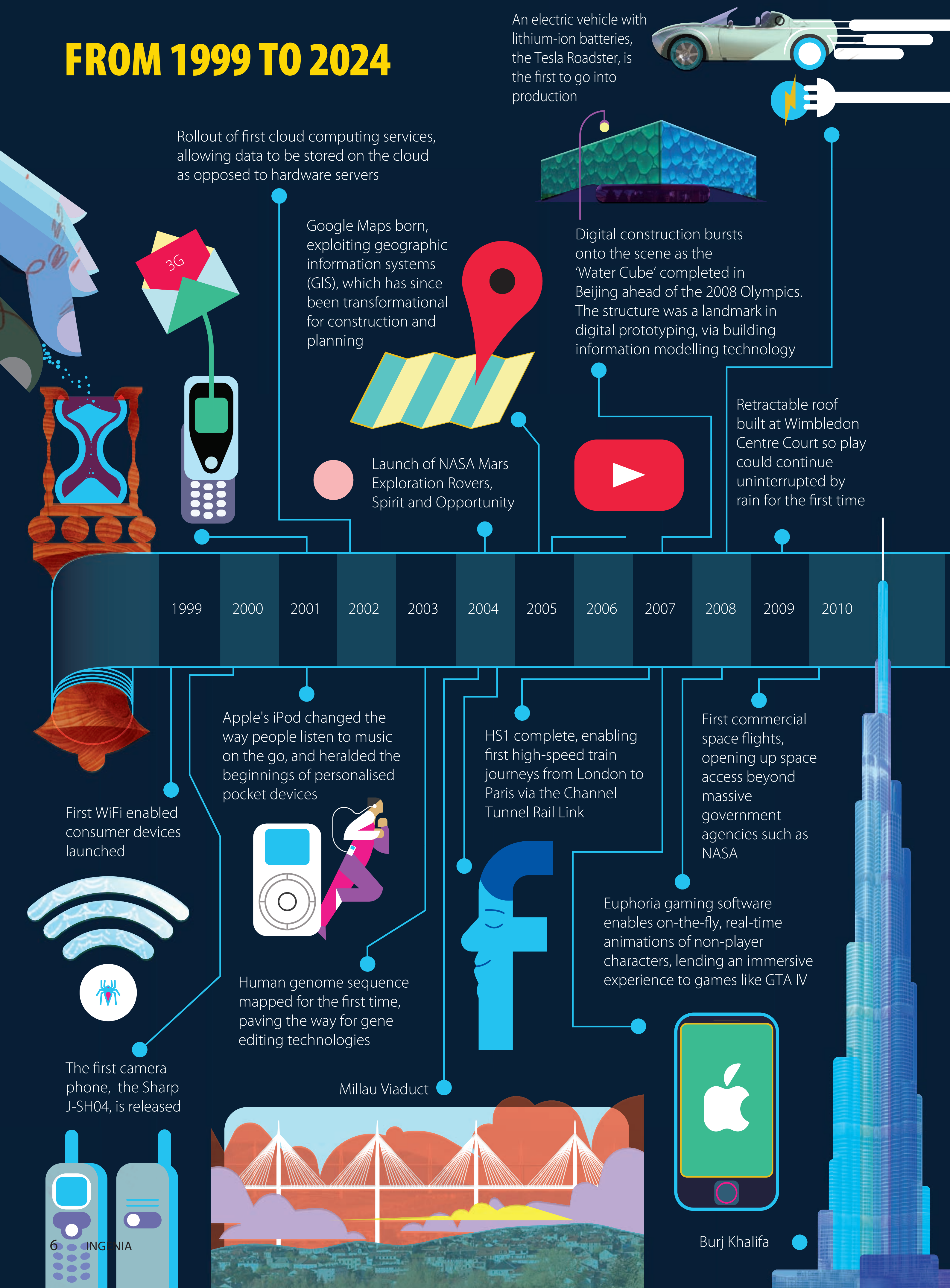
Faith: "We want the website to become a key resource, reaching all areas of engineering and all types of career: something that can be used by young people and parents and teachers – people who influence them."

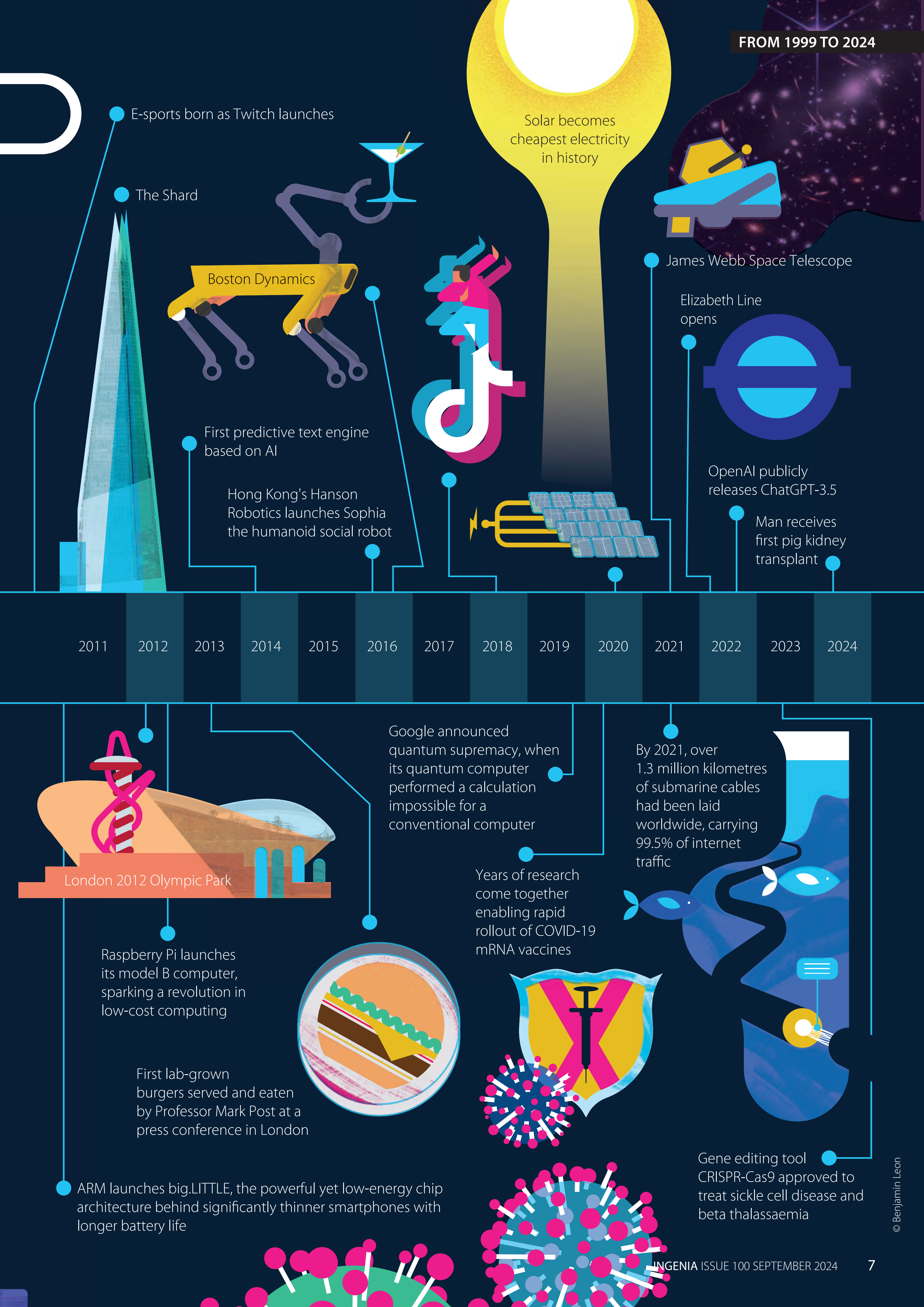
David: "I still think there's a real need for something like *Ingenia*. The thing that it does, which other engineering publications maybe can't do, is that it can be a neutral advocate for the whole spectrum of engineering."

Faith: "*Ingenia* is a pan-discipline, pan-career magazine that truly illustrates the breadth of what engineering is. It's not just news and it's not the learned articles that are peer reviewed, but it is accessible, in-depth material that can pick up somebody's interests and take them much further into understanding engineering."

Scott: "*Ingenia* is like a flower. Or a firework. It should open up new ways of thinking to people who may never have thought about engineering before."

FROM 1999 TO 2024




E-sports born as Twitch launches
The Shard
Boston Dynamics
Solar becomes cheapest electricity in history
James Webb Space Telescope
Elizabeth Line opens
First predictive text engine based on AI
Hong Kong's Hanson Robotics launches Sophia the humanoid social robot
OpenAI publicly releases ChatGPT-3.5
Man receives first pig kidney transplant
2011
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2023
2024
Google announced quantum supremacy, when its quantum computer performed a calculation impossible for a conventional computer
By 2021, over 1.3 million kilometres of submarine cables had been laid worldwide, carrying 99.5% of internet traffic
London 2012 Olympic Park
Years of research come together enabling rapid rollout of COVID-19 mRNA vaccines
Raspberry Pi launches its model B computer, sparking a revolution in low-cost computing
First lab-grown burgers served and eaten by Professor Mark Post at a press conference in London
Gene editing tool CRISPR-Cas9 approved to treat sickle cell disease and beta thalassaemia
ARM launches big.LITTLE, the powerful yet low-energy chip architecture behind significantly thinner smartphones with longer battery life
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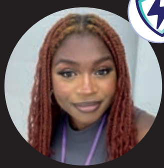
OUR ENGINEERING HIGHLIGHTS

We asked *Ingenia* contributors to share the engineering that's impacted them since 1999. Why not share your thoughts too using #IngeniaMag?

NYASHA MUTEMBWA | Graduate civil engineer, Amey



Panellist at the Ripple Effect conference, championing EDI and youth empowerment in engineering

"As someone born in 1999, this is a very difficult question because so much has changed. The James Webb Space Telescope changed the way people thought about and saw the world. If that's possible, what else is? It made us care about our little planet much more."

CATHY CRAIG | Founder, VR athletic training startup INCISIV

World's first academic to use VR for studying decision-making in sports

"I would say the smartphone. Although the touch screen and built-in camera were not so revolutionary in themselves, they acted as a catalyst for the creation of countless apps that have transformed how we work, rest, and play."

JUDITH MCMINN | Founder, neurotechnology startup Rezon

Developed Halos®, a protective headband for contact and collision sports that reduces concussion risk by 74%

"Up to 40% of brain injuries are classified as 'mild', but brain trauma in sport can be a serious injury that's hidden in plain sight. New brain imaging techniques have unveiled 'silent' brain injuries that previously would have gone unnoticed. More sophisticated neuroimaging allows for the development and determining the efficacy of brain protection like Halos®"

WILLIAM WEBB | Telecommunications engineer

Changed the way that wireless communications carry data by inventing variable modulation

"The iPhone changed completely the way that we interact with the Internet. It allowed the iPad to emerge and showed how touchscreens should work. We now couldn't live without them and that's all down to the user interface and business model that Apple pioneered."

RAYMOND OLIVER | Chemical and biomaterials engineer

Nearly 50 years in engineering, focused on materials, biology and multidisciplinary collaboration

"Precision genetic engineering tools have emerged over the past two decades, thanks to nanotechnologies and biotechnology coming of age. This has led to the 'engineering' of molecular gene editing through CRISPR and advanced generative AI made real."

WILL STEWART | Photonics and optical fibre engineer

Invented the standard method of fibre index profiling, which determines the performance of optical fibres and how light propagates in them

"There really is no serious alternative to the internet here. I would also nominate the optical fibre, which carries 99% of data to smartphones (including WiFi)."

DR RAHUL MANDAL | Technical Lead, Nuclear AMRC, University of Sheffield

Former *Great British Bake Off* winner; baked a working clock cake with fellow Bake-Off stars Andrew Smyth and Giuseppe Dell'Anno

"The advancements in safety as well as efficiency in the nuclear sector have already improved the energy situation in many countries and will resolve the existing and future crisis of affordable energy."

LAURA TUCK | R&D Team Lead, Washing Machine Project

Previously worked on Elvie, a wireless and wearable discreet breast pump, and Peequal, a sustainable 'squat' urinal for women

"A significant rise in women in engineering over the past 25 years has driven essential progress in 'femtech', from advanced breast pumps to female-centric crash test dummies. Women in engineering have had profound influence over women's health and technology in this time."

© Benjamin Leon

JAMES ROBERTS | CEO and co-founder, m0m incubators

Won 2014 Dyson Award and 2023 Princess Royal Silver Medal

"The event that truly amazed me was SpaceX successfully completing its first vertical landing. It was incredible to watch, and everyone I knew who witnessed it for the first time had their jaws wide open."

GINNY CLARKE | Civil engineer

First woman appointed as the UK's Chief Highway Engineer

"Real-time traffic flow information from monitoring and modelling has transformed travel and the logistic industries in terms of reliability. It resulted in just-in-time deliveries and more reliable travel information to customers for delivery of goods."

KHADIJAH ISMAIL | Aerospace engineer

Self-published three STEM books for children

"Companies like SpaceX and Blue Origin have transformed what was once the domain of governments into an arena of innovation and possibility. Reusable rocket technology has significantly reduced the cost of accessing space."

NORAH MAGERO | Mechanical engineer and renewable energy consultant

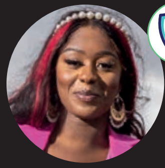
Won the 2022 Africa Prize for Engineering Innovation for inventing a solar-powered fridge designed to improve access to vaccines

"I truly believe that solar energy has made the greatest strides in global impact. Many countries and industry players have actively shifted towards clean energy and solar photovoltaic technology has quickly evolved to provide varied opportunities for access, building economies and livelihoods."

SO, WHAT'S NEXT?

Ingenia contributors proposed the engineering advances that could change the world in the next 25 years. What do you think?

ENENI BAMBARA-ABBAN | Robotics engineer and creative technologist



Founder of The Techover Foundation, supporting those from underserved backgrounds into STEM

"AI integration in robotics will enable talking robots that can learn on the fly, make their own decisions, and collaborate with humans in ways we haven't even thought of yet. It's an awesome time to be a robotics engineer – the future is promising and the possibilities are endless!"

ISABELLE PICKETT | Wells engineer

Attended COP27 as a Youth Delegate and now leads the official European youth delegation at conferences all over the world

"Cleaner energy production will be driven by advanced materials and smart infrastructure, such as digital twins powered by AI. These developments will help manage resources more effectively and reduce environmental impact, ensuring the engineering industry adapts and thrives in a changing energy landscape."

SABINA BURMESTER | Principal Process Innovation and Design Engineer, Xampla

Co-inventor of multiple patents on novel processes to create new products in the food, printing and automotive industry

"Innovation in sustainable materials is key to reducing our impact on the environment. Developing novel materials will rely on close collaboration between scientists and engineers to creatively problem solve and allow for economically viable processes to be scaled up from lab through to manufacturing."

WILL ARNOLD | Head of Climate Action, the Institute of Structural Engineers

Contributed to design of the Rwanda Institute of Conservation Agriculture, the world's first regenerative university campus

"Construction materials that will heal the environment. They might resemble today's building materials, but be created in positive ways. Or they might be new, with foundations made from upcycled wind turbine blades, clad in algae and energy-generating polymers, and filled with finishes made from fungus."

IAN NUSSEY | 53 years at IBM as a systems engineer and skunkworks manager

Former IBM Academy of Technology EMEA VP; won the 2016 Royal Academy of Engineering President's Medal

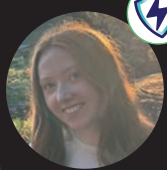
"Blockchain, quantum computing and AI will enable agriculture industry engineering innovation to mitigate sustainability threats. Bioengineering will transform planting, growing and harvesting. Complementary breakthoughs will foster vertical farming and hydroponic practices, operator-free automation, climate management and energy harvesting."

PROFESSOR YULONG DING | Energy materials and process engineer

Inventor of a cryogenic energy storage technology and an in-process CO_2 splitting method for closed-carbon-loop ironmaking

"Long duration cryogenic energy storage will be critical for storing energy from renewables, so that it can be fed back into the grid when the sun isn't shining and the wind isn't blowing."

AVA GARSIDE | CEO, Perfect Sense AQ



Became CEO of her company aged 14 after inventing a graphene-based badge that detects unsafe levels of air pollution

"By unlocking graphene's potential through high-quality and sustainable water desalination, engineers can ensure access to clean water for a growing global population facing an uncertain water future."

CAROLINE HARGROVE | Chief Technology Officer, Ceres Power

Developed the first computer simulations for Formula 1; Ceres Power won the 2023 MacRobert Award

"Decarbonisation of our energy systems and a significant reduction of energy consumption per head worldwide will allow us to live more sustainably. Electrification will continue at pace where practical, and we will see increased use of green hydrogen, e-chemicals and e-fuels, and sustainable aviation fuel."

AURELIA BRZEZOWSKA | Computer science student at Staffordshire University

Finalist for Inspirational Youth Awards' STEAM Personality of the Year 2024

"With quantum simulations and brain-computer interfaces, researchers will understand neurodegenerative conditions better, leading to possible cures."

"Imagine a future where space tourism is a reality."
KHADIJAH ISMAIL

MICHAEL KENWARD | Writer on science and technology

Former fusion researcher and editor of *New Scientist*, contributor to *Ingenia* since 1999

"Next 25 years? Fusion! But that was the promise 50 years ago, when I started as a fusion researcher. Failing that, realisation that net zero is a systems thing. No 'silver bullet'. Just lots of neat technologies."

HARRISON STEELE | Associate professor in synthetic biology

Mechanical engineer turned synthetic biologist. Won Young Engineer of the Year Award, 2023

"Our improved understanding of biological systems will translate to new possibilities in engineering them. This is already delivering benefits to medicine, and in the next 25 years, we'll see some of these technologies scaled up for major global challenges in sustainability and climate change."

HOW I GOT HERE

Q&A

ABIGAIL BERHANE
AEROSPACE ENGINEERING RESEARCHER

Abigail sets up an experiment by placing a total pressure pitot into its holder in her experimental rig

Ingenia guest editor Dr Shini Somara chats to Abigail Berhane about how sci-fi films first got her interested in STEM and a future in engineering was cemented by a visit to CERN. About to hand in her PhD, Abigail plans to continue her work in aerospace engineering to help increase diversity in the field and work towards a greener future.

WHY DID YOU FIRST BECOME INTERESTED IN SCIENCE/ ENGINEERING/STEM?

Physics was always my favourite subject in school, and my fascination with space only deepened my interest. I admire physicists like Brian Cox and Neil deGrasse Tyson, who have a talent for making physics both fun and accessible.

As a child, I enjoyed sci-fi films such as *The Core* and the *Back to the Future* trilogy. Watching *The Core* for the first time, I immediately thought, "I would want to be the scientist who detects something is wrong and the one who gets sent on the mission!" The idea of time travel in *Back to the Future* was also incredibly exciting to me.

My father, a pharmacologist, also played a crucial role in fostering my love for physics. His encouragement was key in my decision to delve more into this fascinating field.

DID ANYTHING IN PARTICULAR INSPIRE YOU INTO ENGINEERING?

In 2014, I had the incredible opportunity, as a Year 11 student, to join a sixth-form trip to CERN in Geneva, Switzerland, to visit the Large Hadron Collider. During our visit, the collider was under maintenance, allowing us to safely explore the experimental areas. Witnessing the engineers at work was truly inspiring.

HOW DID YOU GET TO WHERE YOU ARE NOW?

During my time at the University of Sussex, I found myself really enjoying thermal power cycles. My dissertation was all about designing a casing recirculation treatment for a turbocharger compressor, and thanks to Professor Martin Rose and Dr Vasudevan Kanjirakkad, I discovered a real passion for turbomachinery. While studying, I also worked at Southern Water as a data analyst, keeping track of the efficiencies of various water pumps.

I decided to dive deeper and pursue a PhD in turbomachinery aerodynamics. That's when I came across the Centre for Doctoral Training (CDT) MRes and PhD programme in future propulsion and power, which is a collaboration between the universities of Cambridge (Whittle Laboratory), Oxford (Osney Laboratory), Loughborough (National Centre for Combustion and Aerothermal Technology), and industry partners.

Shini says:

Those who work hard and are committed to overcoming barriers and obstacles to succeed are inspiring to me. Individuals with determination and optimism are my friends. Abigail is one such person, who has diligently persevered with her PhD despite being from an underrepresented group in aerodynamic engineering. Her passion for her area of research and focus on her thesis is to be admired.

When I visited the Whittle lab during my application process, I met Dr Masha Folk, who has been an amazing mentor ever since. She invited me to the CDT Women in Aerospace dinner at Oxford in 2019, where I got to meet some incredible women in the field. After completing the MRes, I started my PhD in 2020, focusing on how surface roughness affects the aerodynamic performance of aero-engine turbine blades.

Since then, I've been lucky enough to receive the Amelia Earhart Fellowship, the 2023 Freeman Award for my contributions to the lab, and the 2024 Cambridge Society for the Application of Research PhD Student Award. Most recently, in June 2024, I presented my research at the American Society for Mechanical Engineers Turbomachinery Conference.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

During my time at Cambridge, I have won awards for my contributions to aerospace engineering, which have all exceeded my expectations of what I could achieve academically. Being the only Black research student at my lab currently and, most probably, the first Black woman to get a PhD from the Whittle lab, I have had to overcome barriers that many underrepresented people face. I am proud to have made a dent, highlighted issues and set an example for other underrepresented people in advanced engineering research in the future.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

I enjoy applying rigorous analysis to complex problems such as surface topography friction and seeing their impact in wider contexts. I really like using novel computational and experimental techniques to understand complex flows in turbomachines. I also want to continue supporting the next generation of diverse engineers. This support is crucial in advancing sustainable solutions. I also want to develop my career in aerospace engineering research because, ultimately, I feel that protecting our environment through my area of expertise is the most personally fulfilling.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

My daily routine depends on whether I have experiments lined up. If I do, I start with a workout at home or at the gym, then head to the lab by 10am for a three-hour cycle of wind tunnel experiments. After lunch, I spend another three to six hours collecting data, depending on how things are going. During this time, I might also do some 3D printing and prep content for the undergrads I supervise.

Once I'm done in the lab, I go home for dinner. My evenings are usually spent processing data, planning the next day's experiments, and making predictions about the results. Now that I'm writing my thesis, I have a lot more flexibility in my schedule, which is a nice change.

WHAT WOULD BE YOUR ADVICE TO YOUNG PEOPLE LOOKING TO PURSUE A CAREER IN ENGINEERING?

Work hard and stay curious. Engineering is an incredibly exciting field. If you're a young woman aspiring to enter engineering, remember you don't have to change who you are to fit in. I've always embraced my 'girly' side, and I still do. Outside of engineering, I'm passionate about textiles and fashion. Diversity is crucial in engineering; it drives innovative solutions to some of our toughest challenges, like climate change.

Academically, engineering combines maths, physics, design and technology, and computer science. Mathematics is all about practice! Don't get discouraged if it's tough at first—keep practising and pushing yourself. Use technology to aid your learning – there's a wealth of information available!

WHAT'S NEXT FOR YOU?

After submitting my PhD thesis this September, I plan to continue my research and publish more papers. In the near future, I hope to transition from civil aero-engines to space flight. My ultimate dream has always been to work in space.

QUICK-FIRE FACTS

Age: **26**

Qualifications: **BEng in mechanical engineering; Master of Research (MRes) in future propulsion and power; PhD in future propulsion and power**

Biggest engineering inspiration: **American mathematician and rocket scientist, Mary Jackson**

Most-used technology: **Polyjet 3D printer**

Three words that describe you: **Curious, passionate and empathetic**

OPINION

HOW CAN WE REIMAGINE BUILDING PERFORMANCE?

The built environment – and what we need from it – plays a large role in everybody's lives. But how do we measure its performance, especially in the face of pressing challenges such as the climate crisis? Here, Fiona Cousins, President of the CIBSE (the Chartered Institution of Building Services Engineers), shares the key points from her presidential address looking at how we reframe the idea of building performance.

Engineers are trained to solve problems. Many of us are members of professional bodies, whose charters require that we act for the good of society. As I started my presidential year at CIBSE, I have been thinking about the problems that we are working to solve and how we connect our everyday work to our broader impact and influence.

Good problem-solving and design needs a clear understanding of the problem, followed by a creative, iterative process, grounded in expertise, that tests different solutions against the requirements. In times of change – and the pace of change is more rapid than it has ever been and will never be as slow again – the definition of the problem keeps changing. In engineering work, the boundaries of the problem are hard to find because everything we do has social, environmental and economic impact. The problems we are trying to solve tend to be both messy and wicked: there is no one right answer, just better and worse, and even these judgements depend on perspective and time.

Looking at this through a building services' lens, we concern ourselves, every day, with building performance. But what is building performance? What do buildings do for us? What should buildings do for us? These are surprisingly hard questions to answer. We are all so embedded in the built environment that, like a fish in water, we struggle to describe the impact of our surroundings.

What we value from our buildings, and how much we value it, depends on our personal circumstances – when things are tough, we seek protection from the weather, and then start to enjoy the benefits of running water, sanitation and power. As we relax into the easy availability of those services we seek security, comfort, and control. We then have time to think about the broader impacts of buildings on climate, our physical health, our human interactions, and the natural environment.

What we value from our buildings also depends on the world around us, especially once our basic needs are met. Buildings and the built environment are expensive, long-lasting, carbon intensive in both construction and operation, and form the backdrops to our lives. For some of these issues the way in which we measure value is unclear, because of both a lack of measurables and inherent subjectivity, and we like to have measures, to be able to manage.

As engineers, we must challenge ourselves both to understand the breadth of the problem and to draw boundaries for the problem that allow us to be pragmatic and make progress.

For problems of this kind, there is a general prescription, outlined in three steps or attitudes.

Firstly, we must be curious about the problem and its solutions. This will help us make the connection between our small decisions and their bigger impact. For example, we have historically focused our ideas about building performance on cost and comfort, and more recently, on carbon and individual wellbeing, driven at first by aspiration to sustainability and more recently by legislation. In future, our thinking will likely need to encompass biodiversity impact. The connection between our decisions and their impact can feel indirect.

Secondly, we must share what we know and listen generously to others. Engineering infrastructure is often meant to be invisible, and the result is that most people do not give it a second thought. At the same time, no single person can understand all the impacts of a project or intervention. Pulling in other perspectives is not easy, but it's essential to view wicked problems through multiples lenses, especially in a world of constant change.

And thirdly, we must be brave. When we look back, even just a few years, we can see that what we consider to be good has changed, as we look forward, we need to drive change in a direction that creates long-term benefit for our society. Driving change is hard – doing things in new ways will often meet resistance and carries risk – and we will sometimes have to defend pragmatism over perfection, but we must lean into change to meet our social obligation.

Applying this prescription to our area of activity led CIBSE to start to reimagine building performance. We used futures techniques to broaden our thinking about the world and to challenge our problem definitions, we reached far outside the industry to get different perspectives on buildings and dug deep within it to make sure we had understood what is technically possible. We also had to spend some time explaining why we wanted to take a broader look and what the impact could be.

The work led us, or perhaps led us back, to an understanding that health and resilience are the ultimate drivers of building performance. This, in turn, allowed us to reframe issues of building performance in its larger context using four themes:

- Variety: recognising the dynamic demands on built spaces – indoors and outdoors – to serve different uses, and different groups.
- Connectedness: buildings do not exist in isolation. How do we work with utilities and infrastructure so that, for example, buildings can be active participants in decarbonising our energy grid?
- Readiness: how do buildings reduce risk and build capacity to support communities when they encounter extreme events?
- Emergence: being open to reshaping our approach in the light of new developments, especially related to materials and energy. Imagine a future 'nutrition labelling of building produces'.

These themes are expansive and challenging, helping us make the connection between the detailed problem-solving we do every day, and the issues that we must deal with as a society.

I invite you to follow up on this discussion – see more in my Presidential Address for CIBSE – and feed back thoughts via ***ingenia@raeng.org.uk*** *or by tagging* ***@RAEngNews*** *and* ***#IngeniaMag*** *on X.*

BIOGRAPHY

Fiona Cousins has worked at Arup since 1989 and is currently Arup Americas Region Chair, a member of the Arup Group Board and an Arup Fellow. Her built projects include the US Embassy in London, Fulton Street Station in New York and the Frick Chemistry Building at Princeton University. Fiona is the 2024–25 President of CIBSE.

HOW ABBA VOYAGE WAS MADE

Agnetha, Anni-Frid, Björn and Benny returned to the stage in East London thanks to ABBAtars based on motion capture technology, massive LED screens and some not-fully-disclosed trickery © Dirk Lindner, Stufish

Shini says:

The engineering steals the show here (or is as exciting as the show itself). I grew up listening to ABBA, so this article takes me right back to my childhood. What an incredible fusion of entertainment and advanced technology. And to think that the building is central to the show's success, demonstrates how infrastructure often takes centre stage. This show has been a roaring success in London, but for me, engineers who make it happen, are the winners who take it all!

ABBA said they'd never tour again. Bringing them back required a technological marvel, a fully demountable arena, and an array of engineering disciplines working in tandem to make it all come together. Leonie Mercedes goes on a voyage to explore the engineering behind the show.

Seven times a week, 3,000 people, many fabulously garbed in the seventies' finest fashions and adorned in sequins, arrive at Pudding Mill Lane station in East London. Their destination: a time machine. After entering the time machine, a hexagonal building more than 25 metres tall, they head to its bowl-shaped auditorium. There's a sense of expectation hanging in the air.

Then the show begins. Live musicians play beyond a vast wall of screens that bring every one of those 3,000 audience members closer to the action. In front of those screens, four performers sing, dance and play through a set list of 22 greatest hits. The revellers can see and hear the performers, but they're not actually there. Now in their seventies, the performers are hundreds of miles away.

This is *ABBA Voyage*, the immersive concert that has let millions experience see a facsimile of what the group looked like 45 years ago in their heyday. The show takes place in a 'flat pack' structure, thought to be the largest demountable concert venue in the world. When the party is over, everything can be packed into storage containers and shipped to another destination.

The project was the product of eight years of collaborative work of teams of engineers, architects, contractors, and thousands of visual artists based all over the world. Many of the project's achievements were world firsts. So, how did they do it?

YOU CAN DANCE, YOU CAN JIVE

The first step was to faithfully replicate the unique way the band members moved to their songs, otherwise the illusion would be shattered. "It's like a fingerprint," said show producer Svana Gisla in an interview at the Beyond Conference in November 2023.

So, for five weeks in the winter of 2020, the four members of ABBA – Agnetha Fältskog, Anni-Frid Lyngstad, Björn Ulvaeus, and Benny Andersson – reunited to perform every song to be included in the show in a motion capture studio in Stockholm. Show producer Ludvig Andersson (Benny's son) described how 160 cameras captured "every mannerism, every emotion, the soul of their beings". He added: "It is not a version of, or a copy of four people pretending to be ABBA, it is actually them."

Behind the cameras were Industrial Light & Magic (ILM), the company that has provided visual effects for almost every big-screen spectacle you can think of, including *Star Wars*, *Jurassic Park*, and the Marvel Cinematic Universe movies. According to Gisla, *ABBA Voyage* was the biggest project the company had ever worked on, calling upon the skills of about 1,000 visual artists from four of its global studios. Ben Morris, ILM's creative director, described the performance capture as "the basis for the whole of the project, the backbone".

In a motion capture studio, performers wear special suits dotted with small spherical markers on particular positions on their bodies. These markers are covered in reflective tape, says Martin Parsons, creative lead at the University of Bath's Centre for the Analysis of Motion, Entertainment Research and Applications (CAMERA). CAMERA uses motion capture for gait analysis in elite sports, and to drive the motion of characters in virtual reality scenes.

An array of cameras surrounds the performers, to identify and triangulate the markers in the 3D scene. To pick up the markers, the cameras can only 'see' black and white, and to replicate motion smoothly, they typically capture the action 120 times per second. The system is calibrated to understand where all the cameras are in relationship with each other, so it can work out where all the dots are in space, Parsons explains.

As a first step, the performers will make their own personalised 'skeleton' by performing a range of motion, Parsons says. The system, knowing

The Institute of Structural Engineers recognised the arena as a 2023 winner of its Structural Awards, for "celebrating modular, demountable timber at scale"
© Dirk Lindner, Stufish

where it expects to find the markers on the performer's body and in relation to one another, fits a template to identify the markers. It can then create a digital skeleton to map onto a 3D animated model, or 'asset', to drive its movements.

After the motion capture, it was back to London, where choreographer Wayne McGregor got to work translating ABBA's physical 'fingerprints' to a group of dancer body doubles. This would imbue the digital imprints of the original band members with their younger, 1979 energy. But it goes further than that: "It's way more than choreography," Gisla said. "It's finding physicality and weight in people."

She added: "It's one thing creating an object, but to make that object crash or to make that person move, let alone dance and perform and stomp, and for that connection to the floor to ripple into the body… that DNA of movement."

The show's producers wince if you call these so-called ABBAtars 'holograms'. They're not nebulous likenesses that look like they could fade away. They appear touchable, from their hair to their rhinestone-encrusted outfits.

Like many of the methods employed to create the show, exactly how ABBAtars are rendered on stage is a secret, though some commentators have suggested that like other so-called hologram concerts, they're using a variation of an illusion called Pepper's ghost.

In this parlour trick first seen in the 1860s, an angled pane of glass divides the stage into two areas – one that the audience can see and another that remains hidden. The hidden part of the stage contains the brightly lit performers, whose life-like reflection is seen by the audience on the angled glass. It works because glass becomes more reflective the darker the area behind it becomes – this is why you can use your phone screen as a makeshift mirror when it's off, but not so much when it's illuminated.

Three 65-million-pixel LED TV screens behind the virtual performers – the central one showing what's happening on stage, the two flanking ones providing close ups of the band's faces – seamlessly blend the physical and digital.

The final piece of the ABBAtars' puzzle was, of course, their faces. But to capture the vast suite of expressions of the performers' faces, motion capture's markers can't go far enough. Here, the effects rely on facial recognition techniques. In facial capture, head-focused cameras capture anchor points on the face, Parsons explains, as well as the texture of the skin. Similarly to motion capture, the information captured by the cameras is used to create facial maps that then drive digital assets. To Benny and Björn's dismay, this process required that they shave their beards. "Is there no other way we can do this?" Bjorn recalled saying, in an interview about the process.

Now complete, the ABBAtars needed a space to perform. It would be an arena like no other.

MASTERS OF THE SCENE

"With a typical design, the building comes first, and the show comes in second and fits into the building," says Ewa Hazla, who was an engineering design lead on the project at structural engineering firm Atelier One. However, the very specific needs of this project required that the show and the venue were created in tandem.

Its ambitious requirements included the need to seamlessly blend the digital and physical on stage, including the lights, sound and other effects. It would have to ensure flawless sound quality inside, while not disturbing neighbours just 65 metres away. Finally, it had to be possible to disassemble and pack the show away – planned after *ABBA Voyage* completes its run in 2025. To pull this all off would take a highly coordinated effort between architects, engineers and contractors.

Atelier One worked with entertainment architects Stufish to develop the structure, its envelope and the front canopies. This was based on a lightweight steel skeleton covered with two layers of timber panels that provide thermal and acoustic insulation. Inside the building, cross-laminated timber (see box) panels make up areas for front-of-house, including bars, retail, cloakroom spaces, and the VIP lounge, as well as providing the finish. A rainscreen of 1,400 finger-jointed fins of larch, a naturally durable and waterproof timber, envelops its exterior.

Timber was the star material of the arena, saving on the building's embodied carbon emissions as no additional finish was needed © Dirk Lindner, Stufish

Lightweight, cost-effective, and with lower embodied carbon than other building materials, timber was the star material of the arena. "Timber offered a better solution than any alternative material," says Hazla. "We wanted to make an effort to incorporate as much timber into the project as possible." Choosing cross-laminated timber also sped up the installation process, she explains, as once the panels were in place, the spaces were effectively complete – no additional finish required. "It eliminated use of materials that just don't work for demountable design, like plasterboard, which can be damaged during assembly or transport, and would need to be replaced at the next install."

Inside the theatre, the design plays a substantial role in merging the digital and the physical. "It's all about geometry," Gisla explained. "It's about sight lines, it's about height, it's about distances, it's just math," she said. "The stage has got be a certain distance from the screen, there's got to be a rake [a stage that slopes upwards from front to back], the audience can't be too high, they've got to be lower than the lights, there's got to be multiple lighting, it's all about geometry."

Overall, it took about a year to assemble, although Hazla estimates that it will take half as long next time, and half as long again to disassemble. The need to eventually disassemble was a factor in every decision about design and materials. With traditional construction of permanent buildings, you only consider that first build, Hazla says: "You generally don't consider how they would be taken away. In our case, every design decision, every detail, every material choice had to factor into not only how that element goes in, but also how does it come out."

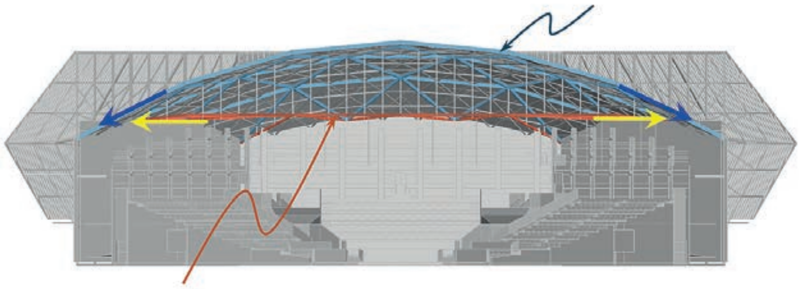
They also had to think about how robust the different components are, so that they will stand up to travel and repeated assembly. "Every single

SOS: A GUIDE TO DIFFERENT TERMS AND TECHNIQUES

Cross-laminated timber: An engineered wood made of layers of timber glued together. "The alternating layers are at 90 degrees to one another in terms of the grain," Hazla explains. "It means that you've got strength in both directions."

Rainscreen: In construction, a rainscreen is a wall that sits away from the interior wall to stop too much water coming into contact with the building itself. This gap both provides a space for water to drain away, and ventilation to speed up the drying of any moisture. The ABBA Arena's rainscreen, created by timber specialist Xylotek, was fire treated, stained, and incorporated an insect mesh.

Finger joint: A joint used to attach lengths of timber to create longer lengths. Several 'fingers' are cut from the end of each length and interlocked (much like how you'd interlace your straightened fingers), held in place by a glue. As each of the rainscreen fins had to reach four-storey heights, Xylotek made every one of the 1,400 individual lengths in Bristol before sending them to London in 204 panels. The total length of the fins is about 15 kilometres.



The tied dome structure creates a strong platform to bear the load of the show equipment in the roof © Atelier One

material choice, every single fixing and detail on this project had to be checked," she adds.

Sound was another crucial consideration in the design of the building, requiring excellent sound quality, soundproofing and reduced noise in a light, robust structure. Working alongside Stufish and design and construction teams, acoustic consultants Charcoalblue developed a two-skin layer equipped with vibration isolators. Generally speaking, vibration isolators reduce unwanted noise by the use of springs or compressive mounts. This avoids rigid connections between the inner and outer skins, and improves the overall acoustic performance of the auditorium shell.

This acoustic layer extended to the building's roof, which contains all the lighting, mirrors, loudspeakers, lasers, and smoke machines. (Hazla explains it is standard in such venues for show equipment to sit above the audience.)

Sitting on top of the drum-like structure of the building's external walls, the roof had to be as light as possible. Atelier One developed what is known as a tied dome structure, which provides an elegant solution to two problems: it both reduces the horizontal force of the roof on the walls of the arena and creates a strong platform to bear the load of the show equipment. "We explored many, many forms for the roof," Hazla says, adding that the tied dome offered the most efficient way to span the distance with the least material.

The key is the horizontal ties, which pull inwards from the edges of the dome to hold it in place. The tension in these ties provides the strength for the platform. The same principle is at play with tied arch bridges.

The roof was built at ground level. This made loading the show equipment much more straightforward, not to mention safer as there was no need to work at height. It also meant that they could construct the roof at the same time as the perimeter structure, Hazla says.

Contractor ES Global raised the roof into place with lifting devices called strand jacks. These lift loads by the action of a hydraulic cylinder on a pair of clamps holding a bunch of cables – no need for cranes or heavy machinery. Strand jacks were attached to 18 points on the roof and the building's primary columns to lift the 70 metre-wide, 750-tonne structure from ground level to crowning glory in a matter of days. "It was absolutely immense," Hazla says.

HERE I GO AGAIN

At the time of writing, the show is due to play in London until May 2025 before heading to its next location, although Gisla has indicated the show might go on for longer (also hinting at the possibility of new arenas appearing in cities in North America and Oceania).

The building has more than enough life in it to support shows for years to come. It has no shorter lifespan than any permanent building, says Hazla. "From a structural perspective, the maintenance requirements have been very minimal," she says, also noting that with the right maintenance and repair, it could last even longer than a typical permanent building.

Which is food for thought: if demountable buildings like these can offer the durability of more permanent structures while being less carbon-intensive, can they play a greater role in decarbonising the construction industry?

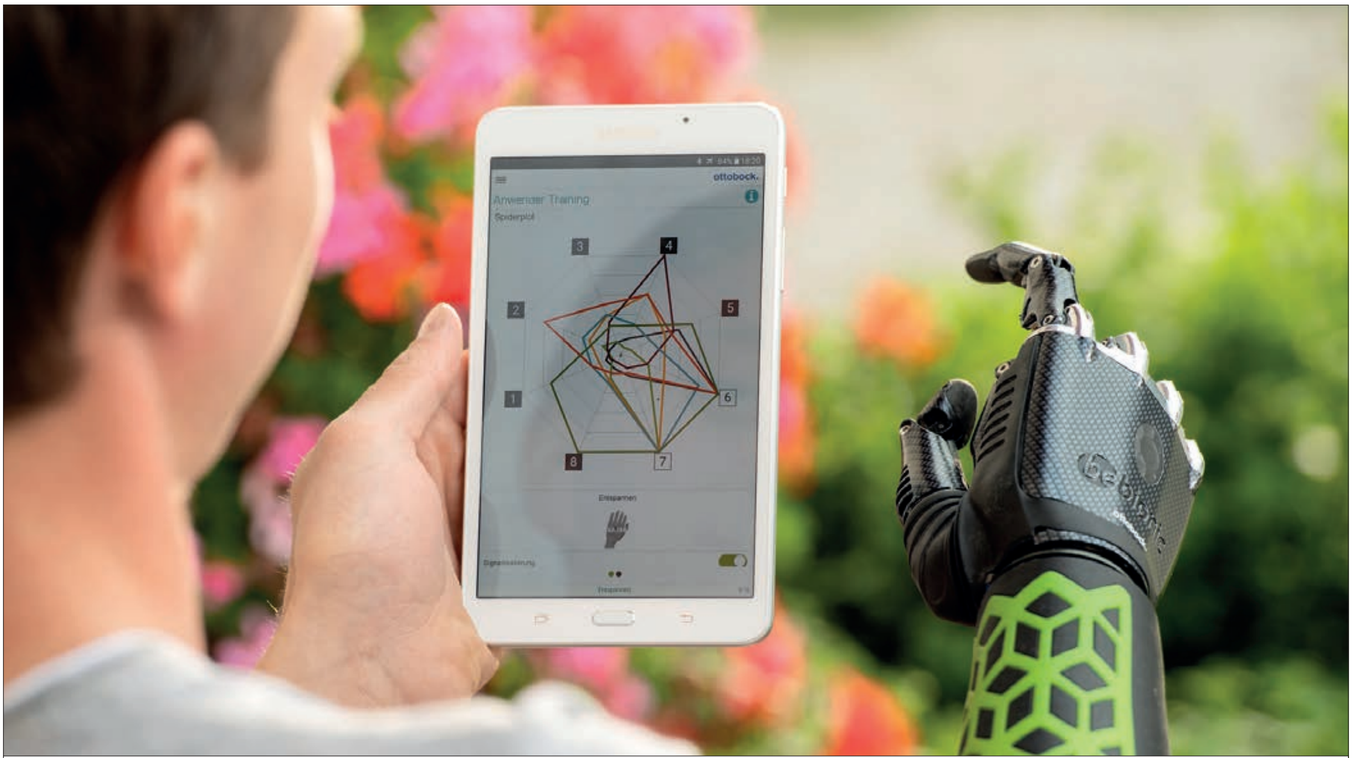
For Hazla, the answer is yes. "We should adopt this approach more ordinarily for permanent buildings, and consider reuse and what happens to the building at the end of its life right from the start," says Hazla.

When the *ABBA Voyage* building does finally close for good, the site will be just as it always was before this time machine descended, allowing another structure to take its place, perhaps. After every last cross-laminated timber panel, screw, and lightbulb is packed away, it will leave without a trace. Except for the odd danced-off sequin, of course.

BIOGRAPHIES

Ewa Hazla ran the day-to-day structural engineering design of the project at Atelier One alongside Aran Chadwick, the company's director, also working closely with principal contractor ES Global, acoustic consultants Charcoalblue, and project manager Gardiner & Theobald.

Martin Parsons, Creative Lead at the University of Bath's Centre for the Analysis of Motion, Entertainment Research and Applications, is a fine art graduate and Emmy Award winner, with 30 years' experience in visual effects. He is currently engaged in research into the future of computer-generated moving image technology.



Ottobock's myoelectric prosthetics now incorporate AI so that people with upper limb differences can control the devices more intuitively © Ottobock

MACHINE LEARNING BOOSTS MEDICAL DEVICES

As AI becomes more widespread, medical devices are among the everyday technologies that could see real improvements. Stuart Nathan finds out how engineers are incorporating AI into hearing aids and prosthetic arms.

Before generative AI and chatbots such as ChatGPT came onto the scene, other kinds of AI were quietly transforming all kinds of industries. In healthcare, bioengineers have been exploring how machine learning – a subset of AI – can improve medical devices and diagnostic tools, and even accelerate drug development.

In the last year, NHS trusts have developed several potentially lifesaving technologies based on machine learning. One system can analyse CT scans to improve cancer diagnosis and treatment, while another based on facial recognition can detect the quality of organs for transplant. Other equally important developments support doctors by preparing X-ray reports or reading blood test results, ultimately freeing up their time for more direct patient care.

Outside of the hospital, engineers are also exploring how machine learning can improve medical devices such as hearing aids and prosthetics. It could solve common complaints that people have with such devices, with the potential for noticeable improvements in day-to-day quality of life.

HEARING AIDS THAT MIMIC THE BRAIN

From adaptive noise cancellation in earbuds to voice recognition in smart speakers, many everyday technologies involve applying AI to sound. It's

Shini says:

Biomedical technology has already come so far. Incorporating AI into these impressive technologies enhances their capabilities to greater levels of precision and efficiency. It's exciting to learn how AI can increase bespoke medical care and therefore its effectiveness. And AI is allowing these innovations to be made available to us sooner.

Starkey has incorporated its Genesis AI hardware into its invisible hearing aids (which are fitted in the ear canal and cannot be seen on the outside of the ear), as well as larger models of its hearing aids © Starkey

no surprise, then, that hearing aid manufacturers use similar approaches to improve devices for wearers.

According to the Royal National Institute for Deaf People, 7 million people in the UK could benefit from hearing aids, but only about 2 million people use them. So, why the gap?

One of the major barriers stopping people wearing hearing aids is a lack of perceived benefit. For example, a big issue is distinguishing speech in loud environments such as in a crowded room or next to a busy road. Older devices tend to make everything louder, which is unhelpful for the listener and sometimes a downright unpleasant experience.

Today, medical device engineers integrate AI into hearing aids in the hopes of solving such problems. Starkey, based in Minnesota, has developed a range of hearing aids that selectively amplify conversation above background noise, even when that includes music with vocals.

To understand how this new generation of AI-enabled hearing aids work, it's useful to look back over the devices' history. The earliest form of electronic hearing aid was simply a microphone connected to an amplifier, which effectively turned up the volume on the signal it received and delivered

ALL ABOUT ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) refers to a broad set of technologies that enable computer systems to perform tasks that would ordinarily require human intelligence, such as voice and facial recognition, analysing data and making decisions.

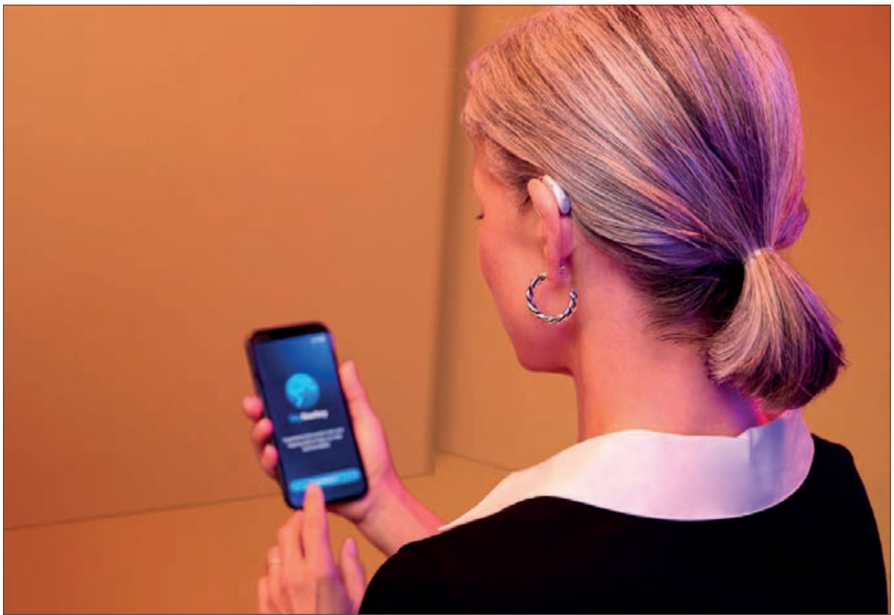
Machine learning is a subset of AI in which algorithms – "recipes" of mathematical operations – find patterns in large libraries of data. It can tirelessly sort through data around the clock to undertake tasks that humans would find tedious or onerous. Thanks to its pattern-spotting abilities, it is increasingly being used in healthcare, where huge databases, often gleaned from studies of many patients, can yield valuable insights.

Neural networks are types of machine learning models that mimic the human brain's approach to processing data.

Generative AI is AI that can generate new content such as written material, imagery, videos or other data in response to prompts. To do this, it first studies massive libraries of training data for patterns and relationships using machine learning, before generating new content with similar characteristics.

Large language models (LLMs) are the machine learning models used for generative AI. For example, GPT-3.5 and GPT-4 are LLMs, available through chatbots such as OpenAI's ChatGPT and Microsoft's Copilot.

Machine learning could solve common complaints that people have with hearing aids and prosthetics, with the potential for noticeable improvements in day-to-day quality of life



Starkey's Genesis AI range of hearing aids link to a connected app, with which wearers can adjust settings, stream calls, and even translate languages and find lost hearing aids © Starkey

this through a speaker in the wearer's ear. The problem with this simplistic approach is that hearing loss is not uniform over all frequencies. Amplifying the entire signal amplifies noise, along with important components such as speech.

The next generation of hearing aids gave wearers more control, thanks to a tuneable chip called a digital signal processor (DSP). These chips convert the sounds captured by the hearing aid's microphone into a digital signal that can be filtered or processed. With the DSP, audiologists could program the hearing aid to amplify specific frequencies. In practice, the audiologist fitting the device would test their patient's hearing to determine which sound frequencies they could no longer hear and program the hearing aid to amplify only those.

"That technology has dominated for the last 10 to 15 years," explains Achin Bhowmik, Starkey's Chief Technology Officer. However, it didn't help wearers surrounded by sounds with overlapping frequencies. Trying to clearly hear the people nearest to you in a busy restaurant is one example. It becomes even more difficult when there is music playing or if the room has echoes.

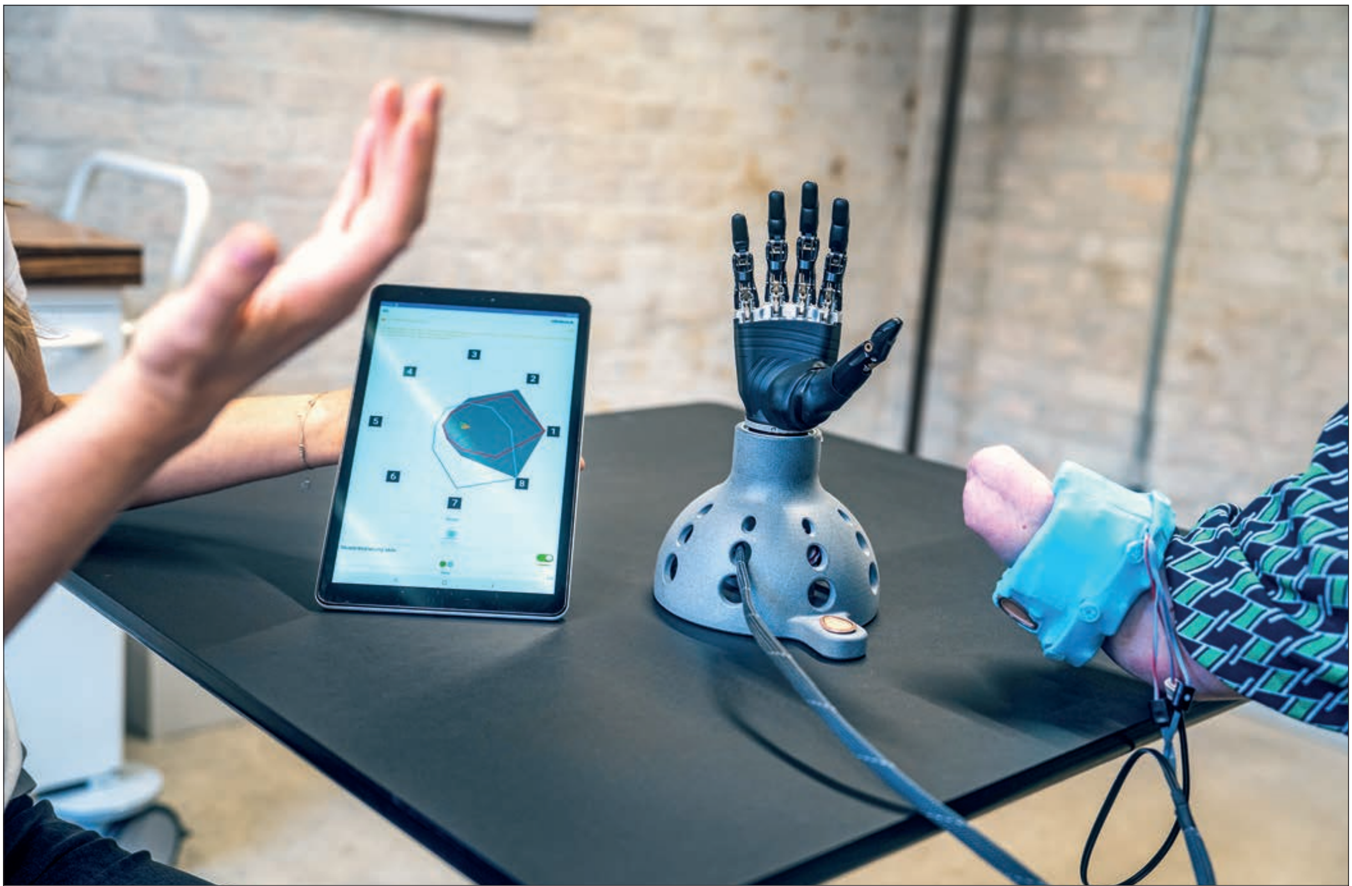
These scenarios cause problems because of the way that the brain processes sound. After sound is funnelled through the outer ear, it is initially processed in the inner ear before being sent to a part of the brain called the auditory cortex. Each of the roughly 100 million neurons in the auditory cortex are connected to tens of thousands of others. If a particular connection between neurons – called a synapse – is used a lot, it becomes stronger. This is what happens when we learn something new. Conversely, if it is used less, it weakens. Neuroscientists believe this is part of when we forget something – and is how the brain stays efficient.

This effect is at play when someone's lived with hearing loss for a while. And according to Bhowmik, it is usually the case, as people tend not to immediately realise that they have hearing problems. "They sometimes find that when they get a hearing aid everything is louder, but they can't understand it as well as they used to," he explains. This is because the amount of signal being sent to the auditory cortex has decreased, weakening the synapses. The effect is particularly noticeable in situations where there is a lot of background noise. Unconsciously, we "forget" how to listen.

To help people distinguish the voice of who they're talking to from background noise, most modern hearing aids preferentially amplify sounds coming from the direction the wearer is facing. They do this by having two microphones instead of one, which helps determine where sounds are coming from relative to the wearer. By comparing the strength of the signals received by the two microphones, it can selectively amplify sounds coming from directly in front of the user. For example, when both microphones receive a signal of equal strength, the sound is coming from the direction the wearer is facing (which is more likely to be something the wearer wants to pay attention to).

Starkey's Genesis range of hearing aids adds an extra layer of AI processing to this to help the wearer to distinguish which parts of the signal they want to concentrate on and understand.

Central to this is a special type of processor chip designed specifically to run AI algorithms called neural networks. In neural networks, signals are treated like they are in the brain, says Bhowmik. When an artificial 'neuron' receives a signal, it processes it and sends the modified signal to other neurons. Just like with synapses, frequently used pathways become stronger, or in computer science parlance, their 'weight' increases. Lesser



Calibration of Ottobock's myoelectric prosthetic hand takes place when an individual first receives the devices © Ottobock

used pathways have a lower 'weight'. This adjustment in weights is analogous to learning.

To determine the weight, the chip is trained with a variety of sounds, including speech and typical background noises in the same frequency range, like wind and the sound of machinery. As a result, it can pick out the exact frequencies of speech and amplify those in preference to non-speech frequencies. According to Bhowmik, this allows wearers to better distinguish sounds that fall in the same frequency range. This could not be done well with the previous DSP-based technology, he adds.

You might think that so much processing would render the hearing aids very power hungry. However, with many neurons – or rather, their electronic mimics – handling signals simultaneously, power consumption is reduced. In the case of the Genesis hearing aids, this means the devices can run for more than 50 hours on a full charge, twice as long as devices not using neural networks.

Another reason why the battery life is so long is to do with the chip's physical structure. "For good battery life, it's best to have the DSP and neural network all on one powerful chip," Bhowmik explains. This is because all of the processing happens in one place, rather than it being shuttled back and forth between different units.

While this technology aims to directly mimic one of the ways in which the brain's sensory systems works, other AI systems are fine-tuning how people can control prosthetic devices attached to their bodies.

PROSTHETIC ARMS THAT BETTER ADAPT TO WEARERS

According to a 2018 NHS review, about 55,000 people in the UK have limb differences. Those with upper limb differences might choose to wear a body-powered, passive or bionic prosthetic arm.

The majority of bionic prosthetic arms are myoelectric: controlled via electrical signals produced by contractions of the upper arm muscles. Typically, these signals are picked up through the skin by sensors in the socket of the prosthetic. This isn't a new technology – it first appeared in prosthetic arm prototypes in the 1950s and 1960s – but still has a way to go before it works for every person with a limb difference, all the time.

To operate a myoelectric arm, individuals must learn new patterns of muscle contraction that will produce hand movements such as making a fist or rotating the hand. But the signals received by the prosthetic's inbuilt sensors must always be the same for it to work consistently. In reality, the sensors can give different readouts over the course of a day for the same input from wearers. This can happen if the wearer's residual limb swells, contracts or gets sweaty because of temperature changes as it can shift slightly in the socket. Signals can also change as the wearer gets tired.

Prosthetics manufacturer Ottobock, headquartered in Germany and Austria, hopes to solve these challenges. The company has developed a myoelectric prosthesis that uses AI to ensure that its performance is consistent throughout the day. Ottobock pairs the prosthetic with what it calls "MyoPlus control", so that the hand's fingers and thumb can hold objects in different ways. Since 2022, the NHS has supplied this AI-enabled prosthetic to people without a lower arm, whether they'd had an amputation or were born with a limb difference.

Martin Wehrle, a product manager at Ottobock, wears one of the prostheses because he was born with a limb difference. After a good night's sleep, "I usually wake up super-energised, put on my arm and everything works fine," explains Wehrle. "But if I'd been on a long flight or had a late night, it won't work so well." Over a day, depending on what he's doing, "the arm's performance starts to get a little worse."

With previous non-AI enabled arms, Wehrle would have to work harder to contract the muscles in his residual arm to get the hand to make the movements he wanted. With the MyoPlus control arm, "it evens out differences in the myoelectric input, even if my skin is dry or it's cold outside, which can have an effect, compared with how the signals are once my muscles have warmed up." The arm also adapts to changes in signal if his muscles start to get tired or sweat starts to build up on his skin inside the prosthesis socket.

The key is a difference in the control protocols. "In a conventional myoelectric prosthesis, we assign a single function to each signal received by a skin sensor, such as open or close the hand, and those instructions are hard-coded into the controller," explains Sebastian Amsüss, the arm's lead designer. "The AI controller doesn't follow hard-coded rules, but rather it adapts to the user." The sensors in the socket detect signals from the wearer's muscles and nerves and 'show' these to the AI system. The AI then uses algorithms to extract the information relevant to that individual that is needed for a specific prosthesis movement.

That "relevant information" comes when the person first receives the prosthetic and it is calibrated to them. "At the beginning, the system doesn't know what to do," explains Johannes Steininger, a software developer who worked on the project. For the calibration, the individual works with a prosthetics specialist who records the different signals that the sensors pick up from the skin of the wearer's residual limb. "We record the different signals the user wants to use to open and close all the fingers, some of the fingertips to the thumb, or to rotate the hand. The AI is then trained to activate the motors inside the prosthesis to produce those movements," he says.

This is very different from how a wearer would learn to use a non-AI prosthetic, Steininger adds. "There's a big variability between how users' muscles work and how their nerve signals look, and whereas before [the wearers would] have to be trained to produce the sort of signals the control system could recognise, now we capture the specific signal pattern of the individual and use that to train the system."

Similarly to how neural pathways can get weaker for a person with hearing loss, amputees who do not begin to use myoelectric prostheses soon after limb loss can lose the pathways involved in hand movement. AI can help to prevent this, Amsüss says. This is because it allows the wearer to continue using the same muscle and nerve pathways as before the amputation, rather than having to learn new patterns. As a result, the synapses remain strong. The closer the pathways are to the ones operating before the limb was lost, the better they are preserved, he says. "Using pre-amputation nerve signals is much more effective than conventional control strategies. This positively affects both the motor and the sensory cortex."

For somebody who has lost a limb, operating a prosthetic by the same parts of the brain that controlled the limb before injury has another important advantage. Rather than feeling that it is "like a brick attached to their arm" – a comparison that Amsüss says some amputees have made – the approach can help them to feel as if the prosthetic is more a part of their body and incorporate it into their mental image of themselves.

We are still a very long way from artificial intelligence replacing human brains, if indeed we ever get to that point. But AI is proving its worth in mimicking some of the ways that our brains function, and using this ability to restore some functions or senses that people might have lost.

BIOGRAPHIES

Achintya K. (Achin) Bhowmik is the Chief Technology Officer and Executive Vice President of Engineering at Starkey. He leads Starkey's efforts to transform hearing aids into multifunctional health and communication devices with advanced sensors and artificial intelligence technologies.

Johannes Steininger is an embedded software developer at Ottobock Vienna and currently lead engineer of the MyoPlus pattern recognition and its successor products. Before joining Ottobock in 2017, he studied biomedical engineering at TU Graz with a focus on machine learning and signal processing.

Martin Wehrle has been Global Product Manager for Upper Limb products at Ottobock Vienna since 2012. Before that, he was a technical trainer at the Ottobock Academy after graduating in electrical engineering from the University of Applied Sciences in Kempten i. Allgäu.

Sebastian Amsüss is a System Engineer and Development Lead at Ottobock in Vienna. In his role, he is the main developer of hand prostheses and is responsible for system integration and interfaces. Previously, he wrote his dissertation on 'Robust electromyography-based control of multifunctional prostheses of the upper extremity`.

THE SMART SENSORS ENHANCING SAFETY

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Manufacturers are increasingly digitising their supply chains to improve efficiency and quality, streamline processes and generally enhance their operations. For production of items such as food, household goods and healthcare products, digitisation is also improving safety. Jasmine Wragg spoke to engineers at the University of York and consumer goods company P&G about how sensors are helping to monitor bacterial contamination.

From the moment that chemicals arrive at factories until an end product is bottled, those on the manufacturing line must diligently follow rigorous cleaning and sanitation procedures on a regular basis to eliminate any chance of microbial contamination. This can lead to undesirable changes in the product, which may lead to wastage and product recalls, as well as losing the trust of consumers. Therefore, manufacturers carry out microbial analysis at every step of the manufacturing process, from the arrival of chemicals to the bottling of the product. This is a vital but time-consuming and resource-intensive process.

As part of the digitisation of its supply chain, global consumer goods company P&G (Procter & Gamble) is using advanced technologies and the Internet of Things (IoT) to make its manufacturing more efficient. As the

Shini says:

Have you ever thought about washing up liquid becoming contaminated during its manufacturing process? I hadn't. I was therefore fascinated to read this insightful article. Ideas, creativity and lateral thinking are always sparked when you learn about something new. And it is often the more inconspicuous problems that offer the most intricate of engineering challenges to solve. And what is really exciting is that solutions can be transferred. This article talks about biosensor technology in a branch of chemical engineering, but who knows where else these innovations could lead!

producer of household names such as Ariel, Oral B, Head & Shoulders, and Fairy, products must meet strict safety regulations and quality checks.

P&G's processes involve regular cleaning and thermal sanitisation of the pipework. Establishing a truly clean state before sanitisation is challenging without the aid of monitoring devices. The company's testing for microbial contamination is typically carried out 'off-line' or 'at-line', where samples are analysed away from the production line – in a separate lab for example – in a process that can take up to three days. The company recognised an opportunity to enhance these procedures in the production of its Fairy washing up liquid in a London-based factory. It actively sought a sensor technology that could be used 'in-line' to directly monitor the inside of the pipes for microbial contamination in real time. By implementing such sensors, P&G technicians aimed to gain accurate information on the product and pipe conditions, focusing the need for external testing. This would allow them to make informed decisions on the cleaning intervals within the factory, reducing manual effort.

SENSING IN INDUSTRIAL ENVIRONMENTS

Sensors and instrumentation play a central role in the transition to Industry 4.0, with increasing use across many industries, including food, agriculture, chemical, and defence, to collect real-time data for monitoring and controlling processes. For example, the data collected in processes such as temperature regulation, pressure control, chemical composition, or bacterial growth can inform quality control, predict maintenance needs, and improve processes. Better control of these processes is also crucial for waste management.

The sensor P&G required had to be reliable, contactless and ultra-sensitive. It also had to be durable enough to withstand the chemicals and pressures in industrial pipes over a long period, as well as low cost for large-scale implementation to be economically feasible.

Many sensors in development are sensitive enough to detect small bacterial fluctuations, but this increased sensitivity makes them more vulnerable to external vibrations and temperature changes, which can interfere with microbial measurements. Vibrations can cause tiny displacements, or misalign optical or electronic components, within the sensor, leading to incorrect readings. This is a significant challenge in industrial settings where acoustic vibrations from pumps, fans and mechanical movements from seismic activity are unavoidable. For sensors that are particularly sensitive, even minute vibrations can introduce noise into readings and affect results. Slight changes in temperature can change a sensor's sensitivity, as sensors are often calibrated to work at a specific temperature. Commercially available sensors that can withstand these environments are generally much less sensitive. After an extensive market search, the P&G team could not find a suitable device and realised that innovative engineering and advanced technology were needed.

INDUSTRY AND MANUFACTURING 4.0

Digital transformation is reshaping the manufacturing industry. The integration of innovative engineering and advanced technologies into the supply chain is known as Industry 4.0. This has led to the emergence of 'smart' factories that use digital monitoring, optimisation and automation in every step of the manufacturing process to boost productivity. For example, predictive maintenance is one such approach. This uses sensors and data analytics to create digital twins – virtual models of physical processes – that can predict equipment failures before they occur and therefore avoid delays in production. Another example can be seen in the use of the Internet of Things (IoT), which connects machines and devices across the factory floor, for seamless data exchange. Manufacturing processes also use artificial intelligence and machine learning to optimise supply chain management, improving aspects such as inventory control. Adopting these digital technologies can help companies enhance their operations, making it easier for them to produce products faster and more consistently. The technologies can save time by quickly detecting problems, enabling manufacturers to make quicker decisions during production based on accurate real-time information. Digital systems also make it easier for them to control process flow, know stock levels and perform quality control.

TURNING TO UK RESEARCH

During the technology scouting process, P&G's external Connect and Develop team became aware of work being carried out by a multidisciplinary team based at the University of York that specialised in innovative sensor technologies, led by Professors Thomas Krauss and Steve Johnson. P&G approached them to adapt their work for a pilot project funded by Innovate UK, and the team eagerly accepted the challenge.

Through the project, the team discovered that some of the sensor technology they had been working on, originally developed for biomedical disease diagnostics, could potentially be repurposed to detect the bacterial biofilms that P&G wanted to target. This technology, a patented optical-sensing device called the chirped guided-mode resonance sensor (chirped-GMR) (see 'Guided-mode resonance explained'), showed promise in early experiments. The next step was adapting it for industrial use and changing its design.

The research team varied the spacing of the grating elements along the length of the sensor. This is comparable to having a row of slits that gradually get closer together or further apart. This 'chirped' design – meaning that the frequency gradually increases or decreases, similar to a bird's chirp – allowed them to represent the spectral signature of the resonance as imaging data. For example, a change in spectrum becomes a change in position on the sensor.

Such a change can be readily imaged with a simple low-cost CMOS (complementary metal-oxide semiconductor) camera. In this way, the chirped GMR sensor combines the sensing and the spectrometer function in a single element.

To address the issue of mechanical and thermal noise that could interfere

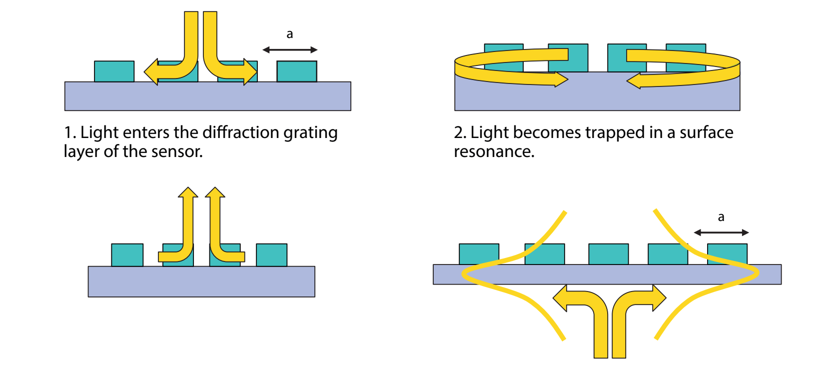
OPTICAL SENSING

A sensor is a device that detects and responds to changes in the physical environment, converting these changes into electrical signals that can be processed to measure different conditions. Optical sensors use light to make these measurements. They are highly sensitive, and since they use light, they don't need to touch the sample, which is ideal for not interfering with the sample environment.

Examples of optical sensors used to monitor manufacturing processes include Raman spectroscopy systems, which detect small frequency changes in light scatter from an object, and infrared sensors, such as those used in pharmaceutical manufacturing to monitor chemical reactions and composition. These sensors are precise and can detect minuscule changes, but they can be expensive and require specialised knowledge to operate.

Another type of optical sensor that is just beginning to be used in process control is the refractive index sensor. It measures changes in refractive index – which is how light travels through a substance – to detect changes in the environment. When the composition of a liquid changes, its refractive index does too. An optical sensor uses a light source to detect changes in the refractive index and convert them into useful data.

GUIDED-MODE RESONANCE EXPLAINED



1. Light enters the diffraction grating layer of the sensor.

2. Light becomes trapped in a surface resonance.

3. Light is reflected to the sensor, in the form of a strong localised wave of energy that can be seen as a signature sharp peak in the reflected spectrum.

4. Some of the light interacts with the environment beyond the sensor. If the refractive index changes (for example, due to the presence of a biofilm), this causes a shift in the peak of the reflected spectrum.

Guided-mode resonance occurs in nanostructured thin films made with layers that can guide light and grating elements that diffract it. Shine a flashlight through a series of evenly spaced slits, and the light will interfere to create bright and dark spots. Reduce the spacing of the slits to the size of the wavelength of light, and the diffraction will direct the light into the grating layer. Moreover, the grating then also acts as a distributed reflector, which sets up a surface resonance. This is when light hits a material and the energy gets trapped on its surface, causing its particles to vibrate in sync. This then creates a strong localised wave of energy that can be seen as a signature sharp peak in the reflected spectrum.

As the surface resonance is formed from multiple reflections that interfere constructively, it is highly wavelength dependent. This is why its signature is a sharp peak in its reflected spectrum. This peak shifts when there is a change in the environment's refractive index, which is how these structures can detect environmental changes.

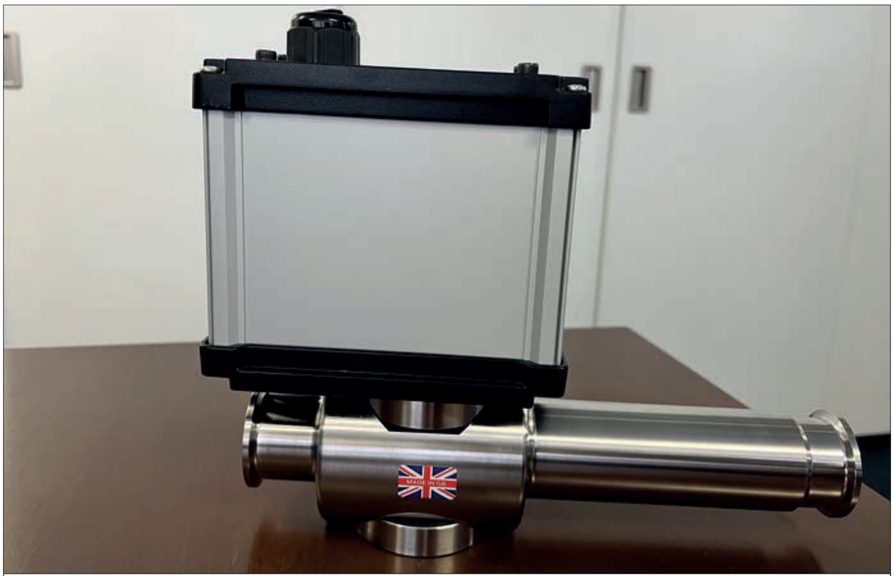
with industry measurements, the researchers changed this grating structure further into a bowtie design. The mirror symmetry of the bowtie helped to cancel out noise from physical disturbances by moving both resonances in opposite directions. When a physical disturbance, such as vibrations, occurs it typically affects both sides of the bowtie equally but in opposite directions, leading to cancellation of unwanted noise. This precise engineering ensured that the signal produced from the sensor was only caused by the change in refractive index.

REAL-WORLD TESTING

Integrating a device developed in an academic setting into the industrial manufacturing process is challenging. The new technology needs to be as reliable or better than existing methods before manufacturers can complete the transition.

The first phase of the project installed the new sensor technology in a controlled environment at P&G's research labs in Reading. P&G's microbiologists intentionally added bacterial spikes with independent experts testing whether the sensors could detect biofilms with the required sensitivity and thus provide early warnings of microbial contamination. The sensors consistently performed well in laboratory tests and were verified by P&G at the pilot plant scale, so now the project has moved to the manufacturing demonstration phase.

According to Andy Dorset, Senior Director of Quality Innovation at P&G, "the manufacturing demonstration phase marks an exciting moment for using real-time in-line sensors to detect microbial contamination throughout the entire supply chain, from suppliers to export trucks. These sensors, connected to a digital platform, can provide insights into how the different parts of the process can potentially impact microbial contamination."



The sensor instrument mounted on a flow-through pipe. These pipes are used throughout the plant to transport liquids between tanks, from tanks to mixers, and eventually to the bottling unit © Phil Marsden

The sensor installed at the top of liquid storage tanks. Installing the sensors in hard-to-reach areas such as these is particularly beneficial. Condensation can form at the top of storage tanks, which could promote more bacterial growth that may otherwise not be detected © Phil Marsden

P&G has installed multiple sensors to monitor the presence of microbes at different stages of the end-to-end Fairy liquid supply chain. The sensors have been implemented at an external supplier in Manchester, as well as throughout the product manufacturing process in London and within trucks that transport intermediate materials to a central European location, where the product is bottled.

Dorset notes the potential of these sensors to replace the current manual methods, describing these as "labour-intensive and sample-heavy". He emphasises that "if successful, this sensor-based approach would provide information much earlier than manual methods. It would enable faster decision-making to address any microbial issues, and also lead to productivity gains by digitising manual and paperwork-intensive processes."

It will take time to complete this phase of the project and the sensors must be able to alert the company to unplanned contamination on the production line to prove successful. P&G has to establish the effectiveness of the sensor-based approach compared to the existing manual microbial analysis before it can consider a complete replacement of the current process.

Dorset further explains that the new approach could affect the organisation's cleaning and sanitisation frequency. "The sensors would serve as in-line monitors, notifying us when we need to take action instead of following a fixed schedule." He adds: "With these benefits in mind our intention is to expand the implementation of these sensors and digitisation to encompass our microbe-susceptible supply chains. This is a pioneering step forward in ensuring product quality in our supply chain."

BEYOND WASHING UP

The York research group has founded a spinout company, Phorest Diagnostics (drawing inspiration from the word 'photonics' – the study of light), to continue developing its patented chirped-GMR technology. This will also allow them to draw on the challenges and learning experience encountered so far.

"Installing the sensor in an industrial setting has been a steep learning curve. We needed to consider not only the robustness of the technology, but also its interfacing with the process control software" explains Professor Thomas Krauss. "Moreover, all the fittings needed to meet Clean Design specifications, which is not something we worry about in the academic setting."

Phorest Diagnostics aims to expand into other industrial sectors beyond washing detergents where in-line bacterial monitoring is essential, such as food production and transport.

"Looking ahead, we are very excited about the prospect of a fully digital supply chain, where process engineers can remotely monitor the quality of product end-to-end, from precursor to finished product," Krauss adds. "To this end, we have already installed a sensor on the truck of a major logistics company."

As industries continue to embrace smart manufacturing, innovations such as the chirped-GMR sensor will play a crucial role in enhancing efficiency, reliability, and overall productivity.

© P&G

BIOGRAPHIES

Andy Dorset is Senior Director, Quality Innovation, at P&G's Newcastle Innovation Centre. He led the funding call with Innovate UK and created the ARGUS consortium. In combination with a P&G team of microbiologists, digital experts and process engineers, this consortium created the first manufacturing demonstration prototype – connecting microbial contamination sensors digitally across the end-to-end Fairy liquid supply chain.

Professor Steve Johnson is Professor in Engineering at the University of York. He leads research into technologies that integrate functional biological molecules with solid-state systems, such as electronic or photonic devices. He has a particular interest in the development of these hybrid technologies to address societal challenges in healthcare and sustainability.

Professor Thomas Krauss is Professor of Photonics at the University of York. He runs a 15-strong group working on photonic nanostructures, how they can be used to manipulate light and how they can interrogate biological processes. He is the inventor of the chirped guided-mode resonance technology used to detect biofilm growth.

It takes 3 kilograms of gunpowder to set off First Light Fusion's two-stage big friendly gun to blast a projectile at a target that contains fusion fuel. The company first achieved fusion in 2021 © First Light Fusion

FUSION ON TARGET

First Light Fusion is setting records in its plans to commercialise nuclear power. Michael Kenward OBE explores how this University of Oxford spinout has taken inspiration from a shrimp to develop a bullet-like process to compress pellets of fusion fuel to create thermonuclear fusion energy.

Fusion power, a long sought-after solution to the world's energy needs, offers effectively unlimited, clean and safe electricity generation that could stay on when the Sun goes down and the wind stops blowing. After many decades of international projects, in recent years dozens of startup companies have raised billions of dollars of private funding in the race to reach what sometimes seems like gold at the end of the rainbow. One of those companies is First Light Fusion (FLF), which has set its sights on using a novel approach to create energy by the fusion of atoms of deuterium (D) and tritium (T), the two isotopes of hydrogen favoured as fuel by fusion engineers.

The venture grew out of research by Dr Nicholas Hawker and Professor Yiannis Ventikos FREng at the University of Oxford. Hawker worked on hydrodynamic simulations of "shock-driven cavity collapse" – what happens when an external shock compresses a target. This laid the foundations for computer modelling to see if that shock-driven collapse would work as inertial confinement fusion (ICF).

Hawker took inspiration from the pistol shrimp. This small creature has a large claw that can click shut so quickly

WHAT IS FUSION?

Fusion, the nuclear process that drives the Sun and the stars, combines two atomic nuclei in reactions that create a larger nucleus, throwing off energetic nuclear 'ash'. In the case of earthbound power generation, the favoured fuels are deuterium (D) and tritium (T), two isotopes of hydrogen. In this case the 'ash' is helium (He) atoms and neutrons. Catching the neutrons and their energy can provide heat to run steam turbines and feed electricity to the power network.

For controlled fusion to happen in a pellet of deuterium and tritium (DT) the fuel must be at temperatures so high that it becomes an ionised gas, a mixture of nuclei and electrons, or plasma. Only then can the DT nuclei overcome their natural repulsion and come together fiercely enough to undergo fusion.

Conventional plasma containers are useless at those temperatures. They would cool down, or 'quench', and contaminate the plasma with unwanted materials that would rule out fusion. However, such is the electromagnetic nature of plasma, with its mixture of positively charged nuclei and negative electrons, that a carefully constructed magnetic field can bottle it up and keep it away from the container's physical walls while fusion reactions take place.

The pursuit of fusion energy has historically involved building increasingly massive machines. The best known 'magnetic bottle' is the multinational Joint European Torus (JET) at the Culham home of the UK Atomic Energy Authority (UKAEA) near Oxford. In the final set of experiments before its shutdown earlier in 2024, JET set a record for the amount of energy created in a hot plasma, a mixture of D and T, the most likely fuel combination for fusion reactors.

The pistol shrimp, which inspired First Light Fusion's approach © Shutterstock

that the underwater movement creates a bubble and a shockwave in the water. As the bubble collapses, the shock wave heats the vapour in the bubble to tens of thousands of degrees, emitting a brief flash of light. The shrimp's aim is that the loud noise from the shockwave will kill its prey.

When modelling the shrimp's trick, and the interaction of the bubble and shockwave, Hawker decided to apply the computer simulations to a pellet of fusion fuel. Could a similar process to that clicked claw create a shockwave to heat fusion fuel to temperatures and pressures needed for nuclear fusion?

FUSION WITH IMPACT

Set up in 2011, FLF is one of a handful of companies using a process known as ICF. FLF describes its variation of ICF as impact fusion. It starts with a small pellet of DT fuel (see box, 'What is fusion?') embedded in a target, which implodes when it is smashed with enough energy. In the process, FLF's targets are designed to work as amplifiers and to compress the fuel pellet from all sides until it reaches temperatures and pressures higher than those in the Sun.

The best-known example of ICF is the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California. Funded by the US Department of Energy and built at a cost $3.5 billion, the NIF – the world's largest laser – officially opened in May 2009. It made headlines in 2022 when it reported that fusion reactions there had produced more energy than it took to heat and compress the fuel targets, one of the major benchmarks for ICF. The NIF uses 192 powerful laser beams as drivers, housed in a 10-storey building the size of three football fields, to blast tiny pellets of DT.

This was good news for FLF. As Hawker puts it: "Our approach leverages the same physics now proven by NIF but combines it with a unique approach that gets to a competitive cost point in a truly scalable manner." FLF's system doesn't need a large array of lasers, just a single fast-moving projectile, launched by a driver at a carefully designed target.

FLF had already built two machines to test its target designs. One, dubbed the big friendly gun (BFG), uses gunpowder to aim a projectile at fuel targets. The second driver, called Machine 3, uses electromagnetic forces to launch a projectile at the fuel.

In November 2021, FLF achieved fusion on its BFG machine. To confirm that FLF had created genuine thermonuclear fusion, it enlisted the help of the UK Atomic Energy Authority (UKAEA). The UKAEA's Culham Laboratory is the home of the Joint European Torus (JET), the best-known example of magnetic confinement fusion. It has a long history of diagnosing what goes on in fusion projects. Its researchers pored over FLF's diagnostic systems and confirmed its claims.

FLF had planned to build an even bigger driver, but the positive results from NIF were a cue to change direction. Ryan Ramsey, Chief Operating Officer, says that as more results came in from NIF they asked themselves "Why are we doing this?". FLF decided to concentrate on developing its 'shock amplification' approach to ICF.

The NIF concept isn't practical for a power plant, says Ramsey. "You can't have 192 penetrations into a reactor chamber." Instead, FLF hits targets on just one side. The target itself then creates a shockwave that compresses the fuel from all sides. "The convergence is created completely within the amplifier," says Hawker. On impact, the pellet itself pushes the fuel to fusion conditions.

When it comes to getting fuel into its targets, the company can draw on the previous experience with ICF. FLF can then put that inside its own amplifiers.

"The key technology for us is the target design," says Hawker. It is, he says, "the secret sauce". When it comes to building a power station, Hawker has compared ICF to an internal combustion engine: drop in a fuel target, hit it with a projectile, recover the energy, and keep repeating the process.

TEST AND AMPLIFY

FLF has tested its approach on the Z Machine operated by Sandia National Laboratories in New Mexico in the US. The most powerful pulsed power facility in the world, the Z Machine can electromagnetically launch projectiles to higher velocities than any other facility.

FLF describes its approach to ICF as being "driver agnostic". The driver just has to hit the target (and therefore the amplifier) hard enough.

Ramsey says with five different ICF driver technologies under development around the world, FLF's approach could be relevant to all of them. Each driver will need different target designs, which is where the company's expertise in accelerator modelling, computer simulations and target manufacturing come into play.

The modelling proved its power in February 2024 when measurements on the Z Machine broke the pressure record. FLF's simulation predicted the pressure to within 2% of the measured result.

'Machine 3', built in 18 months at a cost of £3.6 million, stores electrical energy in banks of capacitors. It uses electromagnetic forces to launch projectiles at the hypervelocity speed needed to test fusion targets. The projectiles hits the amplifier at 20 km/second. The company describes this as "one of the largest pulsed power facilities in the world and the largest in Europe". It is also the only one built specifically for fusion research © First Light Fusion

After keeping its computer modelling and simulation in house, mostly to protect this intellectual property, says Ramsey, the company is now preparing a cloud option to see if this can speed up the development and simulation of new drivers. "The cloud will give us significantly more computer power. We think this will make us quicker," he adds.

For Ramsey, computing has been the game changer in amplifier design. Add machine learning and FLF can devise new amplifiers and analyse how they are likely to amplify the driver's impact force.

FLF's current business plan is to focus on designing amplifiers that others can use in their ICF reactors. To this end, the company is building a portfolio of patents on the design and production of amplifiers.

FLF's amplifiers, cubes of about four centimetres, are made of "normal materials," says Hawker. With model amplifiers to hand, the in-house precision manufacturing team can assess how easy it is to make new amplifier designs. As Ramsey puts it, there is no point in designing a great amplifier if you can't make it.

The company's idea is to design and validate amplifiers and licence production to specialist manufacturers who could make targets in the large numbers, perhaps thousands a day, that a reactor would need. To this end, FLF is investigating the manufacture of amplifiers with the support of the Advanced Manufacturing Research Centre in Sheffield.

BIOGRAPHIES

Dr Nicholas Hawker is Co-Founder and Chief Scientific Officer. His research into fusion began in 2007 as part of his master's thesis at the University of Oxford. This work continued into a DPhil, where he performed hydrodynamic simulations of shock-driven cavity collapse.

Ryan Ramsey, Chief Operating Officer, has a business background in energy, construction and offshore leadership. He has also led in the Royal Navy Submarine Service as captain of a nuclear-powered submarine and taught future submarine captains.

HOW TECHNOLOGY IS RESHAPING FARMING

Robots are increasingly being used for autonomous monitoring and inspection. Here, the robot is checking the ripeness of strawberries but the same set up can monitor for other things such as pest and diseases © Warwick Agri-Tech at WMG, University of Warwick

UK growing conditions for fruit and vegetables are changing all the time in the face of climate change. So, engineers are coming up with ideas to help farmers increase their crop yields in an ever more challenging environment – from robots to monitor and harvest crops, to automated vertical farms that reduce land use. Dominic Lenton takes a look at some of the latest developments in agritech.

Shini says:

The diverse and inclusive uses of cutting-edge technologies in robotics are fascinating. From satellite imagery, machine learning, biotechnology and so much more, technology is essential to improving crop yields and increasing sustainable farming beyond what we are capable of at a human scale. With a planet running out of space and weather becoming more extreme, innovations such as these could ensure that less of the food we grow is not only healthier, but does not go to waste!

After one of the wettest winters on record, UK farms have struggled to cope with the heavy rain that continued through spring and long into the summer. Many farms were subject to flooding, which left crop fields under water and put the health of livestock at risk. The extreme weather, which is linked to climate change, has drastically reduced the yield of key crops such as wheat.

Alongside these pressures, farmers are facing other competing demands, including developing more nature-friendly and sustainable practices, while also keeping costs down in a tricky economic climate.

The previous Conservative government's 2022 Food Strategy suggested that technology may have a role to play in helping farmers face such a challenge. As part of the programme, UK Research and Innovation launched a £270 million Farming Innovation Programme to support R&D projects that benefit farmers, growers and foresters in England. Examples of projects underway include new applications of satellite imagery and machine learning, as well as new vaccines for animals and biotechnologies to be used in livestock breeding. Robots, too, are making waves: along with their potential in filling in for the shortage of seasonal workers, new roles are appearing for them in pest management and targeted application of fertilisers.

However, not all farmers have embraced these new technologies yet, says Charlie Yorke of the National Farmers' Union (NFU)'s primary insurer, NFU Mutual. Results of a survey by the organisation released in January 2024 show that less than 20% of farmers have invested or plan to invest in agritech and 62% have yet to even consider it. But getting started with technology doesn't have to mean investing significant sums in robotics and automation. According to Yorke, lower-cost, accessible solutions, such as gate sensors, RFID eartags (which can be used to track animals) or the integration of an online data administration system, can still make a huge difference to productivity. "While some large farms have invested in complex and large-scale agritech such as self-driving vehicles, alternative fuels and data-driven sensors, it is important to remember agritech can be implemented at any scale, large or small," he says.

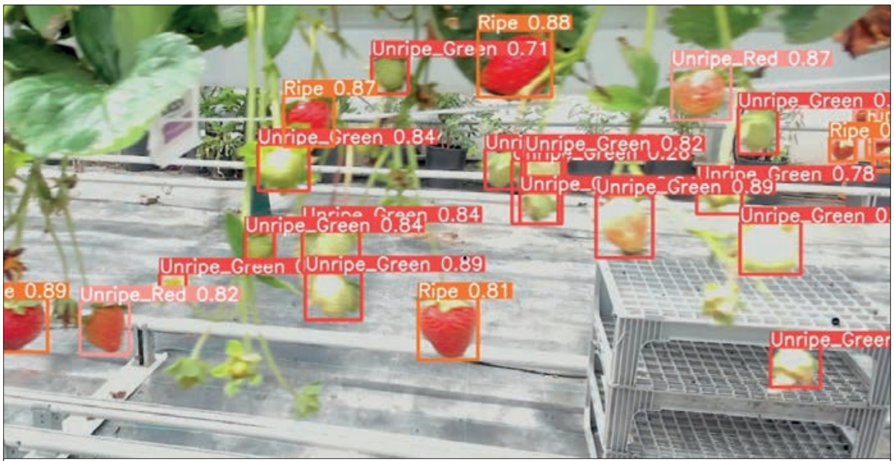
SEND IN THE ROBOTS

The University of Warwick is developing technologies that may give farmers the confidence to take the plunge. In 2023, the university launched Warwick Agri-Tech to combine the facilities and expertise of WMG at the University of Warwick and its School of Life Sciences. The new centre is exploring new technologies to address issues such as labour shortages, food insecurity and biodiversity loss. "It's rare to have access to both the manufacturing facilities we have at WMG and the 220 hectares of farmland available through the School of Life Sciences, alongside the joint expertise," says Alicia Feledziak, Business Development Manager at WMG, High Value Manufacturing Catapult Centre. "Bringing together those two departments unlocks a massive amount of possibilities."

The initiative has its roots in the 'Crombot' crop monitoring robot – a WMG-led project that set out to address growers' scepticism of new technology and, most importantly, its cost. "We understand the challenges that growers are facing," explains Emilio Loo Monardez, Lead of Warwick Agri-Tech at WMG. "Our role is to derisk the technology and create solutions that are modular, scaleable and viable for growers to adopt."

Engineers developed a robot that could check for pests, diseases and crop ripeness – a repetitive and time-consuming but essential task. Crombot, a four-wheeled robot with a robotic arm-mounted camera, can autonomously navigate around a greenhouse to monitor crops, avoid human workers and even follow specific co-workers on command. Once strawberries and other crops are ripe, for example, the robot can also highlight which areas of the greenhouse are ready to be picked.

WMG engineers have also made use of 'Spot', the autonomous four-legged robot dog developed by Boston Dynamics that went viral in 2016, and have adapted it for use in agriculture and horticulture. Spot can walk up and down steps, over heating rails and other obstacles as well as tackle muddy fields with ease, which have all proved beneficial in handling a variety of greenhouse and outdoor environments. But Feledziak points out that – similar to Crombot – its main role was in inspection, with the team building algorithms to monitor variables such as pests or the ripeness of fruits. "The real research is happening in the brain of the robot and how that can be applied



A view of Crombot's computer vision model identifying strawberry ripeness

to different purposes in the agricultural space," she explains.

Autonomous robots such as Crombot and Spot are central to a more data-led approach to improving crop yield. As well as using sophisticated cameras and image-processing technology to accurately monitor when fruit and vegetables are ready for harvest (see 'Fruit-picking robots', *Ingenia* 93), they can reduce chemical use. Robots can identify the exact locations where herbicides and pesticides are needed – and when – so that growers can apply the products directly rather than spraying a whole crop and risking contamination.

For example, engineers at Warwick are developing an AI-based weed-control robot that promises to cut the need for herbicides by over 90% while improving soil health and biodiversity. Currently, when growers apply herbicides, they are sprayed over everything – the run-off is absorbed into soil, killing biodiversity, and also washes into streams and rivers when it rains, polluting waterways and even ending up in drinking water. The APSA (Autonomous Smart Spot-Precision Application of Herbicide) project uses a platform with computer vision to look for weeds, using AI-enabled recognition to identify them. A robot can then distribute targeted doses of weedkiller where needed, so that there is no excess run-off. This approach can also encourage growers to use more sustainable bioherbicides and bioprotectants. These are more environmentally friendly but, because of their lower potency, need to be delivered more precisely to have a comparable effect. "There is a huge amount of pressure to reduce chemical use in agriculture and make processes more sustainable," adds Loo Monardez. "With this algorithm, we'll start with herbicides and then it can be transferred to other weed-eliminating solutions such as laser and electric pulse."

Another project at Warwick is using automated monitoring to tackle spider mites in tomato crops. As a robot travels along and inspects the rows of plants, a hyperspectral camera monitors the leaves. Hyperspectral imaging gathers detailed information about an object's composition and characteristics, in this case picking up changes in how the leaves reflect light. Changes in reflection indicate damage caused by mites, which are small and hide on the underside of the leaves – extremely difficult for the human eye to see and not a viable position for a camera. The monitoring process continuously feeds data on pest levels to a system that ensures that a second line of defence – possibly in the form of a natural fungus-based bioprotectant – is brought into play at exactly the right time and applied only where required.

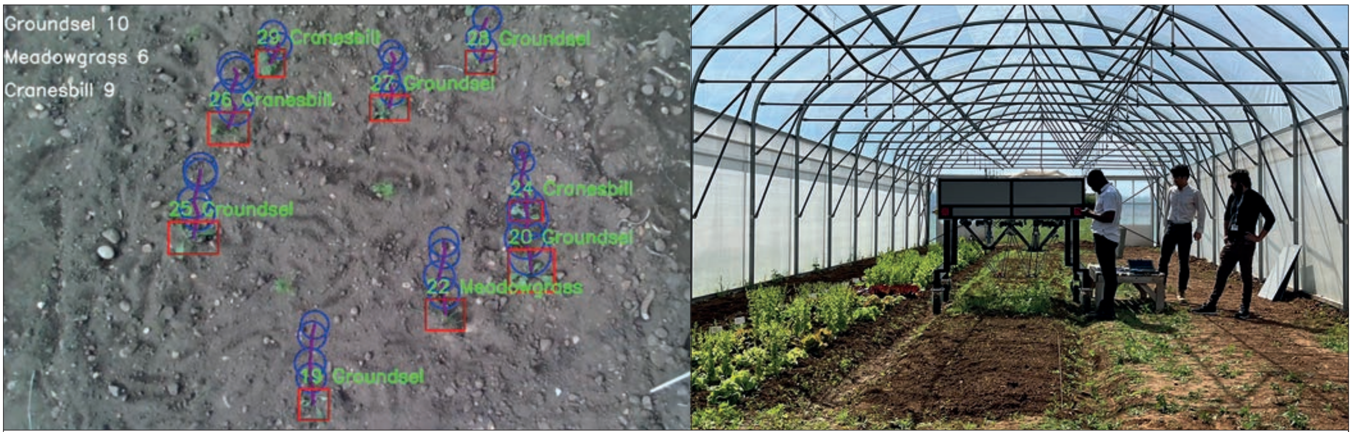
Elsewhere, researchers at the University of Loughborough are also working on an AI-enabled navigation system for use in two projects that are aiming to improve the efficiency of fruit picking in the UK. The £4.5millon Precision Orchard Management for the Environment (POME) project is a four-year venture that will digitally examine and scan fruit trees in fine detail to generate precision-dosing maps for blossom, fruit thinning, fertiliser application, growth regulators, pest controls, and fungicides, while producing more accurate yield forecasts for growers. Its Area-H project has developed a navigation system to help support agricultural autonomous robots in the field. Both projects have received funding from DEFRA and Innovate UK.

REDUCING LAND USE

Autonomous and AI-enabled technologies, like those emerging from Warwick and Loughborough, are designed to work within an environment that resembles a traditional farm. However, engineers have also developed approaches that are transforming the ways in which crops are grown.

Often touted as a way to boost productivity while reducing land use and therefore environmental impact, vertical farms use soil-free growing techniques and stack crops in specially designed beds and trays. As well as minimising the need for water, fertiliser and pesticides, they make carefully controlled use of artificial lighting and climate control.

Edinburgh-based Intelligent Growth Solutions' (IGS) demonstration facility in Dundee is equipped with models of its Growth Tower fully automated platform (see 'Vertical farming for future growth', *Ingenia* 78). Its modular system of stacked trays is irrigated by a central mechanism that employs ebb and flow hydroponic technology – similar to tides rising and falling along coastal areas and estuaries – to pump recycled, nutrient-rich water to each plant. Meanwhile, LED light strips underneath each tray illuminate the plants on the tray below. And the



Computer vision software identifies different species of weed (left) and the autonomous spot application of herbicide robot in action (right) © Warwick Agri-Tech at WMG, University of Warwick

whole system operates hand in hand with HVAC (heating, ventilation and air conditioning) controls to achieve optimal humidity, with condensed water collected, captured, cleaned, and recycled.

The app-controlled environment can grow a broad range of crops, including salads, leafy greens, brassicas, edible flowers, and even fruiting crops such as chillies. IGS claims each unit can yield 20 tonnes of crop in just 40 square metres of floor space rather than an outdoor plot of a hectare or two – roughly the size of two rugby union pitches. Its technology has already been exported globally, to places such as the US, and the company's ambitions continue growing.

At the COP 28 UN climate change conference, IGS showcased a future 'gigafarm' that aims to incorporate hundreds of 12-metre-high Growth Towers. The plan is for the gigafarm to be built on an 87,000 square-metre site in Dubai, where it will grow more than 3,000 tonnes of produce per year. IGS says that it will be 98% more water efficient than growing crops in a field. The facility is expected to be fully functional by 2026 and will support the UAE's move towards decarbonising food production.

IGS's partner on the project is Dubai-based ReFarm – a group of companies that is driving forward the UAE's first zero waste food security initiative. The gigafarm will also recycle more than 50,000 tonnes of food waste, turning it into a fertiliser and soil that can help crops grow in extreme climates. Onsite, black soldier fly larvae will convert food waste into a biomass that is rich in proteins and fat, and byproducts will include organic compost, animal feed for replacing unsustainable fish meal and soy oil, and water for use in the vertical farming towers. The onsite technologies will also recover up to 90% of ammonia sulphate from wastewater for use in plant fertilisers.

Peppermint, violas, parsley, and micro kale grow in one of IGS's Growth Towers © Intelligent Growth Solutions

Closer to home, IGS is part of the V-FAST (Vertical Farms and Storage) consortium, a group of UK companies that has earmarked sites between Dumbarton and Dundee in Scotland for a series of vertical farms, powered by renewable energy. The low hills of the region are ideal for an approach that combines vertical farming with local renewable energy generation and energy storage, often within the same footprint and on lower quality land that is not suitable for traditional farming.

One of the main challenges – for all vertical farms – is the cost of energy. Co-located renewable generation helps, but intermittent availability of wind and solar power means some form of storage is needed to provide the 8 to 12 hours of backup required for vertical farming.

Part of the V-FAST solution is a high-density hydro storage system from partner RheEnergise that provides grid stability while meeting the predictable base energy demand of a vertical farm. The 10 megawatt and 50 megawatt systems operate on a similar principle to traditional pumped hydroelectric storage – where two water reservoirs at

ENGINEERING PLANT GENES

Manipulation of plant and animal microbiomes is helping tackle diseases that can have a significant effect on crop yields. In this emerging branch of biological engineering, scientists are looking for an alternative to pesticides to control bacterial blight. Researchers at the University of Southampton, with colleagues from China and Austria, achieved a first recently when they successfully boosted the prevalence of 'good' bacteria that protect the plant from disease.

The team identified one specific gene found in the lignin biosynthesis cluster of the rice plant, which is involved in shaping its microbiome. Lignin is a complex polymer found in the cell walls of plants – the biomass of some plant species consists of more than 30% lignin.

When they deactivated this gene, there was a decrease in the population of certain beneficial bacteria, confirming its importance in the makeup of the microbiome community. Overexpressing the gene – essentially making too many copies of it – caused it to produce more of one specific type of metabolite (a small molecule produced by the host plant during its metabolic processes). This increased the proportion of beneficial bacteria in the plant microbiome.

When the team exposed these engineered plants to Xanthomonas oryzae (a pathogen that causes bacterial blight in rice crops) they were substantially more resistant to it than wild-type rice.

Dr Tomislav Cernava, Associate Professor in Plant–Microbe Interactions at the University of Southampton, predicts that the technique could have a range of applications: "We've achieved this in rice crops, but the framework we've created could be applied to other plants and unlock other opportunities to improve their microbiome. For example, microbes that increase nutrient provision to crops could reduce the need for synthetic fertilisers."

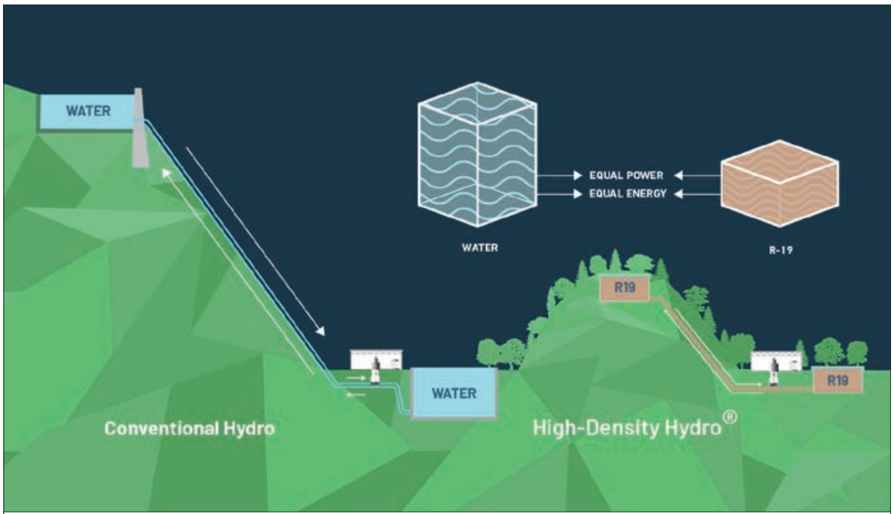


Diagram showing how RheEnergise's High-Density Hydro system works
© RheEnergise

different levels generate power as water moves between them via a turbine. But RheEnergise's system uses a fluid with a density two and a half times that of water, which means it can be installed on small hills rather than tall mountains. Fluid is pumped to the highest storage tank at times of low energy demand using power from renewables or cheap electricity from the grid. As conditions change, the fluid is released and passes through turbines as it descends, generating electricity.

Subject to site investigations, planning and financing, the first V-FAST project could be completed within the next two to three years. With 10,000 cubic metres of vertical farming floor area and 80 megawatt hours of energy storage, it could produce 20 to 30 times as much food that could grow in open fields of the same size.

SECURITY AND SUSTAINABILITY

The use of robotics and AI in crop monitoring and the adoption of vertical farming techniques are a step in the right direction to addressing the pressing challenges of modern agriculture. The UN says that global food production from plants and animals must increase by 70% by 2050 to meet demand, but it is already responsible for nearly a third of carbon emissions as well as significant deforestation.

As Monardez points out these challenges are "bigger than just engineering" but he suggests that multidisciplinary approaches, which combine engineering, plant science and biology, can help the agricultural sector enhance food production while adhering to sustainability goals. The pioneering efforts of UK engineering, demonstrated by initiatives such as Warwick Agri-Tech and IGS, already point to technology and innovation's potential to lead the way.

BIOGRAPHIES

Alicia Feledziak is Business Development Manager for Warwick Agri-Tech at the University of Warwick. Alicia holds an integrated master's degree in mechanical engineering and has industrial experience in manufacturing technology development and factory of the future technologies across both maritime and aerospace. Alicia is now responsible for driving the strategic growth of Warwick Agri-Tech, developing an entity capable of derisking and accelerating innovation for industry for the future of farming.

Emilio Loo Monardez is Principal Engineer and Technical Lead of Warwick Agri-Tech (WA). Emilio has over 15 years of experience in industrial engineering, automation, robotics, and lean manufacturing. Emilio led the creation of Warwick Agri-Tech, and alongside his colleagues, continues to develop its strategy, collaborating with businesses and organisations to support sustainable production of food, aiming to contribute to a stable, sustainable, global food system.

THE CHIP THAT FLOATED A THOUSAND IDEAS


© Raspberry Pi

For Dr Eben Upton CBE FREng, floating the Raspberry Pi business on the London Stock Exchange is another step in a career that has straddled engineering and business. Michael Kenward OBE hears how, in what started as a plan to improve IT education in schools, the world-changing credit-card-sized computer has become a building block for many engineers who want to add intelligence to their products.

Eben Upton believes that his route into engineering was typical for many British youngsters. Schools don't teach engineering, so, like many school students, he graduated from playing with things such as Meccano and LEGO before discovering his true vocation at university. A self-proclaimed "LEGO kid", Upton also grew up when the BBC Micro was popular. Today, Upton is the CEO of Raspberry Pi plc, a business whose products were a way into engineering for many young people. Indeed, there is now a whole community that combines the 'Pi' with LEGO. Upton has also seen a rapid rise in the number of working engineers who use 'Pis' in their work.

There was an earlier hint that engineering would prevail in Upton's GCSE choices at school. He had signed up to for an exam in craft, design and technology (CDT). As Upton puts it: "CDT was the closest you could get to engineering, proper engineering." Then again, he adds, CDT also had a reputation for being "a subject for kids who wanted to skip classes".

That reputation nearly got in the way of his plans. The head of the school's design department rushed into the staff room and said to Eben's mother, who taught at the school: "Eben's signed up for the wrong course. He clearly meant to sign up for CDR." CDR was craft design realisation, which, Upton says with a laugh, "you could caricature as being a nice drawing course". His mother went home and asked him if he'd made a mistake. His response was an emphatic "no, I wanted CDT." Upton was not alone in that decision. "I found out later that everybody who went to Cambridge to study physical sciences or engineering also did CDT."

LEARNING THE CODE

Computing was another early interest. Like many young people in the early 1990s, Upton was into home computing, writing code for various machines such as the Commodore Amiga. He'd left school a year early, at 17, "not through any particular intellect, but just bit of luck". In between school and university, he worked at IBM as a preuniversity employee, alongside people working on different things. Over the years, these IBM alumni have bumped into each other working for different companies and launching startups. "One of my former colleagues from IBM works for me now," he adds.

In Upton's case, the school experience and time at IBM wasn't enough to turn him into an aspiring engineer. He went from school in Leeds to the University of Cambridge to study physics. But that didn't stick. "If your mind wanders at a critical moment, you can't get back," says Upton. For him, statistical thermodynamics was the parting of the ways.

After two years, Upton switched to the engineering department and the Electrical and Information Sciences Tripos (EIST). The degree course was "a lot of fun", he says.

A positive effect of the move might seem strange given Upton's subsequent career as a leading light in computing: he "completely dodged Fortran". This, he explains, was a subject for physics students in their third year but was year two for engineers. When he should have been studying Fortran, a programming language for scientists, Upton was into other computer languages, leading to his first startup company, at the age of 20. The business started off working on graphics technology for the web, moving on to mobile phones and gaming. Now called Marmalade Game Studio, Upton proudly points out that, 26 years later, the company still exists. "I sold out of it a long time ago, but they've been paying people's salaries. Paying tax and generating export earnings." As he describes it "that was the thing that I dropped out of Cambridge to start".

THE BUSINESS OF ENGINEERING

In reality, this was not what most people would call dropped out, it was the beginning of another thread in Upton's career after graduating. He has always been keen on business. "I like business. The business of engineering. It's the thing that is exciting.

"I've always been interested in business. I remember standing in the station in Leeds and looking at all the people walking past with their briefcases and in a hurry … and wanting to be one." You could blame it on TV. "I used to watch *Bergerac*." The TV series featured a dodgy businessperson, Charlie Hungerford. "I shouldn't idolise a slightly corrupt fictitious businessman, but I just really thought he was amazing. He was always doing these business schemes and stuff, and it just always seemed interesting."

In the event, the shine of that first business experience wore off and the lure of Cambridge drew him back. "I didn't particularly want to live in Cambridge and commute to London every day. A year seems like such a long time when you're 22 years old and you're like, 'Oh God, I've been doing

Someone in the next village had a small company making motor controllers for golf buggies. Here was a little technology business making "nice little electronic products for people". Lots of machines needed motor controllers: shunting engines, golf carts and mobility scooters. Upton worked on software for these controllers

this for two years'." So he sold out to the co-founders and went on to fulfil another ambition.

"I had always wanted to do a PhD. I liked the idea of being an academic as well." His father had spent his life as an academic, a professor of English at the University of Leeds. "He had a good run. He enjoyed it."

Cambridge had another attraction. "I knew there is history in Cambridge of academics also doing business." So, he felt like it could be a good place to do both things. Married by then, and with a PhD that was taking longer than it should "because I'm disorganised", he launched a couple of little lifestyle startups to keep paying the mortgage.

A MOVE INTO ELECTRONICS

His next move added what would turn out to be another important ingredient that led to the Raspberry Pi, he learned something about electronics. PhD completed, Upton decided that, after all, academia was not for him. "I'm not even sure it's about intellect. I just don't have the right orientation to succeed in that environment, I need to be making things."

Someone in the next village had a small company making motor controllers for golf buggies. Here was a little technology business making "nice little electronic products for people". Lots of machines needed motor controllers: shunting engines, golf carts and mobility scooters. Upton worked on software for these controllers.

He sees that experience as the last bit of the Raspberry Pi puzzle. "Raspberry Pi is an electronic product that's there to help young people program computers. So, the electronic product bit of it is really important. That was my first exposure to electronics. I'd never managed to make that leap from doing really quite sophisticated software to doing any kind of hardware."

It was a while though before Upton baked the first Pi. He was, in his eyes, bumbling along, until a friend suggested a job interview at Broadcom, a major communications chip design business. Broadcom was a chance to get back to Cambridge, where the company worked on mobile phones. "He tricked me into going for an interview at Broadcom," Upton laughs. He didn't know that lining up a recruit would get the friend get a bonus. "You got a couple of grand if you could lure one of your friends to the company. He has never even bought me a beer," Upton jokes.

Upton maintains that he went along for the Broadcom interview for the laughs. He wasn't interested in a job. That changed at the interview where he met "impressive people who were working on fascinating projects. I came out thinking, 'geez, I would love to work there'." He did, for 14 years. This was at an exciting time in chip world, with the growth of the mobile phone and the rise of 'very graphics heavy' chips.

Broadcom wasn't just a good place to work as a software engineer, it was the final bit of the Raspberry Pi jigsaw. After experiencing the University of Cambridge's problems in recruiting students with IT skills, Upton was becoming interested in doing something about computer literacy among young people. "Raspberry Pi is the result of wanting to give another generation of young people the opportunity to do engineering, and wanting to give them a platform that they could use to discover computing and electronics as a way into engineering in the way that I did.

QUICK Q&A

Favourite project you worked on?
BCM2836, the chip that we developed, at very low cost and on a very short schedule, to power Raspberry Pi 2.

Who influenced your engineering career?
Alan Drew, who drove me to Computer Club in Ilkley every other Friday night when I was a teenager.

What's your advice to budding engineers?
Hang out with smart people. Volunteer for the hardest jobs. Fail. Try again. Repeat.

Which engineering achievement couldn't you do without?
The high-bypass turbofan. Often I'll spend a chunk of a widebody flight just gazing at the engine. Affordable international travel has had such a profound impact on my life.

Overlooked engineering successes?
Inmos, which failed as a company, but set the stage for the UK's continuing ability to punch far above its weight in semiconductor design.

Upton, centre, on the day that Raspberry Pi floated on the London Stock Exchange © London Stock Exchange

The chips we were working on at Broadcom happened to be exactly the right devices to put into a product like that." To this day, Broadcom is the biggest supplier of chips for Raspberry Pis.

A SLICE OF THE PI

With a £20 price tag, the Pi crashed into a market at a time when, if you wanted to play around with computing, you didn't have much choice beyond paying out for a fully fledged PC. As Upton says: "The Raspberry Pi came along and kind of ate my life and ate my Broadcom career. The rest, I suppose, is history." Part of that history was when the Raspberry Pi collected the Royal Academy of Engineering's MacRobert Award (see 'Chips that changed the classroom', *Ingenia* 72).

Recently, Raspberry Pi floated on the London Stock Exchange in July 2024. Upton has been the CEO of the company since it was set up as a trading operation in 2012, separate from the educational foundation that handles that ambition to do something about enthusing young people about IT and engineering.

Why go public after the company has been successfully, and profitably, making Pis for 12 years? "For somebody who's fascinated with business, listing your company on the stock market is a fascinating thing to be involved in. It's a hard thing to do, obviously. It's been a challenging environment to list a company in. That it went well is incredibly gratifying. What surprises me about the whole story really is that I'm still learning."

For Upton, going public with Raspberry Pi was a natural step forward. "You've got the ability for the company to tap public markets for finance, if we need to. Because some of the engineering programmes we do now are enormous. Raspberry Pi five was a $25 million programme." In recent years, the business has been investing about $10 million a year in R&D.

Going public is an opportunity for early investors to recoup some of the money they put into the business, it is also a way to reward staff and provide an easy market for them to trade in the shares allocated to them over the years. "I don't think it's been to the detriment of the purity of the business. We still get to do amazing engineering."

And that engineering has changed in the life of Raspberry Pi. What started off as tool for school students has moved on to being a broader operation. It has also got into chip design in its own right. No longer is it a case of making products based on third-party chips and licensing the IP to someone else to manufacture them. In line with the industry model, it still doesn't have its own manufacturing plant. "We design complete electronic products, and we have them made in a factory that we don't own."

There are two main business activities at Pi. The first is the original credit-card-sized complete PC. There is also a growing business in designing new chips that others can use, but that can go into Pi's own computer modules. "It lets us make cooler Raspberry Pi products."

Since the early days of the Pi engineers outside education have looked at this inexpensive neat little device and seen ways to use them in their own systems and products. The core of the company's business now is selling prefabricated compute subsystems that people integrate into larger products. About three-quarters of the sales of Pi are to the "industrial and embedded" market.

This sort of development needs money. Although Pi isn't gobbling up cash in the nine-figure numbers needed to make chips for AI. Already running late for his next meeting, Upton can't resist responding to a last-minute question about AI and what it could do for the electronics industry and the world as a whole. "Look, it's a tool. It's not AI," he laughs. "Machine learning is much more accurate branding than artificial intelligence. It's just a new thing and continuous improvement on the tools we have."

You could almost say the same thing about the Pi. What started as a tool for classrooms and hobbyists has turned out to be a powerful, exciting, often surprising set of tools. It is also a tool in Upton's transformation from software engineer to business engineer. But that didn't quite work out as planned: the suits and briefcases that first caught his eye on Leeds station seem to be things of the past. Today's meetings are as likely as not to be train free. When we spoke in an online session, Upton was in his office wearing shorts and a T-shirt. As to the briefcase, paperwork has mostly given way to a portable computer of some sort, although there might be room for a pack of Raspberry Pis.

RASPBERRY PIS IN ACTION

When the Raspberry Pi first appeared, it was a surprise hit with engineers who wanted to add some computer power to their own devices and systems. When he noticed this phenomenon, Upton tried to keep track of these unexpected uses. "I used to have a spreadsheet that told me where all the Raspberry Pis were," he says.

Such has been the industry take-up of the Pi that this could now be a full-time job. Industry now accounts for about three-quarters of the sales for Pis.

One of Upton's early favourites was when the son of a Japanese cucumber grower used a Pi to sort thorny cucumbers, saving the farmer eight to nine hours' manual work a day. Seven years on and the business applications of the Pi keep coming.

On your bike: Machine learning meets the Raspberry Pi in Velo AI's Copilot, a device that warns cyclists about vehicle movements behind them. Based on Raspberry Pi's Compute Module 4, Copilot can detect and distinguish nearby vehicles, understand when one is about to overtake, and identify an aggressive or distracted driver approaching dangerously. It then gives the cyclist an audible alert and uses flashing lights to alert the driver.

Hardened for industry: Another Pi favourite is OnLogic's Factor 201. This starts with the Raspberry Pi Compute Module 4 and 'hardens' it for industrial applications, to create systems that survive shock, vibration, extreme temperatures, and airborne debris.

Factor 201 includes devices that handle everything from monitoring premises and critical infrastructure to energy management and process and quality control. As Upton puts it "just quietly keeping some important chunks of the world running smoothly".

Movers and shakers: Another favourite at Raspberry Pi is Raspberry Shake's line of seismometers and infrasound monitors. These devices cover the spectrum of Pi users from education and hobbyists to professional users. It has also been a hit in the world of citizen science.

© Raspberry Shake

Raspberry Shake proclaims that it was "created on the slopes of Volcán Bar in Panama". After attempts to build a seismometer using other platforms, the Panamanian team spotted the rise of the Pi. Plans to raise funds surprised them. Instead of getting a few dozen backers, they ended up with hundreds.

In echoes of the birth of the original Raspberry Pi, the seismologists were flooded with orders and suddenly had to deliver 800 orders. Thanks in part to help from Raspberry Pi itself, including advice on logistics, it worked out and there are now global networks of amateur and professional users of Raspberry Shake devices sharing seismographic data.

CAREER TIMELINE AND DISTINCTIONS

Studied physics and engineering, **1996–1999**, then a diploma in computer science, University of Cambridge, **2000–2001**. PhD in computer science, **2001–2005**. Founder, PodFun, **2004–2006**. Director of Studies in Computer Science, St John's College, Cambridge, **2004–2007**. Distinguished engineer, Broadcom, **2006–2020**. Awarded Royal Academy of Engineering Silver Medal, **2013**. Appointed Commander of the British Empire, **2016**. Elected a Fellow of the Royal Academy of Engineering, **2017**. Founder, Raspberry Pi Foundation, **2008–present day**. Chief Executive Officer, Raspberry Pi, **2020–present day**.

THE ENGINEERS TURNING SURPLUS FEATHERS INTO PACKAGING

London-based startup Aeropowder is turning surplus feathers into a biodegradable thermal packaging material, designed to keep items such as medicines or vaccines insulated and cold during transport. Can nature do it better than plastic?

Elena Dieckmann (left) and Ryan Robinson (right) are co-founders of Aeropowder
© Aeropowder

In a world that's relying on packaging more than ever, manufacturers are increasingly on the hunt for greener alternatives to plastic. It's not easy replacing this uniquely versatile and strong family of materials. In their search, material scientists and engineers have turned their attention and ingenuity to a variety of natural materials, including seaweed, pea and rapeseed proteins, and even … feathers.

Feathers might strike you as an odd choice for a packaging material. But during her master's at Imperial College London, Elena Dieckmann discovered that millions of tonnes of surplus feathers are generated globally every year. Figuring there must be a way to use them, Elena hit upon the need to keep items cold during transport. Known as the 'cold chain', major industries such as the life science and pharmaceutical industries face unique challenges when attempting to transport lifesaving but temperature-sensitive items.

GREENER INSULATION

The cold chain may not get much airtime, but it is critically important for health. An increasing amount of novel therapeutics must be kept within a correct temperature range. If a vaccine gets too warm, it can begin to destabilise and lose efficacy. Lifesaving gene therapy products could instantly be destroyed by the formation of ice crystals if it gets too cold.

Preserving the cold chain can be particularly challenging when shipments must be sent over large distances or to areas with poor 'last mile' logistical infrastructure. The biopharma industry alone is estimated to lose approximately $35 billion annually to temperature failures. To mitigate the risks in these scenarios, companies pack

EYES ON THE INNOVATORS

***Ingenia* is keeping a close eye on the engineering breakthroughs making a difference around the world.**

Google DeepMind won the 2024 MacRobert Award for its groundbreaking, AI-powered weather forecasting technology

Scientists at the **Universities of Edinburgh and Dundee** will analyse 1.6 million brain scans with AI to develop a tool that can predict dementia risk medical products in specially insulated boxes before shipping. These carefully designed solutions work as a package, combining insulation materials plus a coolant, which can include regular water-based materials or dry ice, if you need it *really* cold. (Pfizer used the latter to keep its COVID-19 vaccine at –70°C, which is colder than Antarctica.)

"If you want to ship a measles vaccine to Africa, you really have a very long logistics supply chain, and this is why you need a high-performance insulating material," explains Elena. The current go-to is expanded polystyrene. Sometimes known by its trade name Styrofoam, expanded polystyrene is the plastic foam you might also find cushioning items such as electronics, or sometimes in takeaway cups and containers.

With sustainability in mind, companies are increasingly looking to phase out expanded polystyrene because it is extremely expensive to recycle. Elena quotes a cost of up to $3,000 per tonne, "so, it's not a winning business," she says. "Often [it] just gets chucked into landfill or incinerated sometimes. But there's no healthy end-of-life option for polystyrene as it is." Since hardly anyone is recycling it, that also means consuming more fossil fuels to produce new expanded polystyrene.

Instead of sending all this expanded polystyrene and all those feathers to landfill, why not just use the feathers for insulation instead? With this in mind, Elena and co-founder Ryan Robinson (who is now CEO) set up their company Aeropowder and began developing the product.

THE AVIAN WONDER MATERIAL

"Feathers are actually a real wonder material built by nature," explains Elena. They're at the heart of many birds' mating displays – such as the peacock's – and of course, are essential for creating lift and thrust in flight. As if this wasn't enough, they also protect birds from the elements, providing crucial waterproofing and trapping heat.

These insulating properties are why people have been stuffing pillows and duvets with feathers for centuries. The secret behind feathers' warmth comes down to their material properties. "They're hollow inside, and if you look into the microstructure, they trap air," says Elena. The main shaft of a feather extends from the tip of the quill, with tiny hair-like filaments protruding along its length. In flight feathers, the filaments are hooked together to give a more rigid form. The filaments in down feathers waft unattached from one another, to maximise air trapping and thus, insulation.

CREATING A NEW CIRCULAR ECONOMY

Clearly, you can't just pack a load of feathers into a box and call it a day. With their patented process, feathers are converted into a unique textile mat that can be produced in a variety of shapes and sizes for the requirements of clients.

"Our material intrinsically possesses excellent insulation properties, but like all other insulation materials, performs better when made thicker. This proved technically challenging for a number of reasons, but extra thickness is critical for delivering the required level of thermal performance for a pharmaceutical-grade product," explains Elena. The material is cut to the sizes needed for the packaging box it will ultimately become, and then sealed in a biodegradable and compostable liner for ease of handling.

Aeropowder's first target market for the product was in the direct-to-

To make their insulating packaging material PluumoPlus, Aeropowder processes waste feathers into a thick mat and encapsulates it in a biodegradable liner © Aeropowder

consumer food delivery space, where items such as meal kits needed to be kept cold for overnight delivery. Recognising the potential for their material to finally provide a required level of thermal performance for the higher-end pharmaceutical and life science industries, the company is about to launch PluumoPlus, a sustainable thermal packaging solution that can keep the products inside cold for 72 hours even under challenging industry-standing shipping conditions. This is a game-changing level of thermal protection for the industry, as generally the pharmaceutical industry has struggled to move away from expanded polystyrene given performance deficits of the current crop of sustainable alternatives.

Beyond packaging, Aeropowder has other potential products up its proverbial sleeve, including expanding the use case for its insulation to the construction industry or creating solutions to control oil-spill environmental cleanups. Having just raised £150,000 from the British Design Fund, the future looks bright for Aeropowder and its plans create a new circular economy from a fluffy wonder material.

A boy with severe epilepsy is the first to trial a new device fitted in his skull to control seizures, developed by **Amber Therapeutics**

Plans launched for nine **offshore wind farms** could potentially deliver clean energy to 11 million homes in the UK

Amid declining Braille literacy, **University of Bristol** researchers have developed a pen which can read Braille aloud

HOW DOES THAT WORK?

AIR FRYERS

Air fryers have become immensely popular in recent years, promising a healthier and more energy efficient method of cooking that can save you money. They have also inspired numerous dedicated cookbooks and even a few TV programmes.

According to a September 2023 report published by kitchenware retailer Lakeland, 45% of UK households now own an air fryer, with sales of the appliance outselling deep fat fryers by more than 92 to one at the store chain that year.

Air fryers offer an alternative to deep frying that lets the home cook prepare favourites such as perfectly crisp and delicious French fries with a fraction of the amount of oil. It sounds like culinary magic – how does it work?

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START THE FANS, PLEASE

An air fryer is essentially a convection oven that fits on the kitchen worktop. "The word 'air fryer' is probably a misnomer," says Séamus Higgins, associate professor of food process engineering at the University of Nottingham. "In a lot of respects, it's no different to any other oven, in that what you're doing is heating air to a certain temperature, which in turn cooks the food."

The air fryer's main components are a heating element and a fan that rapidly recirculates hot air around the food – which sits in a basket or on a mesh tray – to cook it. Because of this fan, which spins thousands of times a minute, the heat in an air fryer is distributed more evenly than you'd find in a conventional oven, which tends to be hotter at the top and cooler at the bottom. It also makes cooking much faster.

More controls let the user set cooking time, temperature, or a range of functions such as 'air fry', bake, or roast, depending on what's for dinner. The main differences between the air fryer and a conventional oven are size, the efficiency of the heating element, and the control, Higgins adds.

How is it that this little oven can produce foods that taste like they've emerged from the deep fat fryer… with air?

THE CHEMISTRY OF COOKING

Let's start with what cooking is. Different foods react in different ways when you apply heat – that's the wonder of it. Proteins denature and stiffen (think eggs, meats), starches break down to become sweeter and more yielding (potatoes or porridge, for example) and sugars caramelise into sticky deliciousness (hello, crème brûlée topping).

In the air fryer, foods get the flavour you'd expect from a deep fat fryer due to the Maillard reaction: the browning of the surface of some foods when they reach a certain temperature.

The Maillard reaction – a term that actually describes thousands of different chemical reactions happening in sugars and proteins – produces the flavours and aromas that make food delicious, and is responsible for golden fries, bronzed biscuits and browned meats. It's the layer of oil on the food that enables the Maillard reaction, Higgins says, along with dehydration.

As for that crispness that makes fried foods so irresistible, that's because of dehydration on the surface. As the oil coating heats up, it evaporates water in the food so that it cooks quickly and forms a crispy exterior.

A GREENER WAY TO COOK?

As well as the health gains from cooking with less oil, a big part of the air fryer's appeal is its economy. As there's a far smaller volume of air to heat – about one to six litres compared with about 60 litres for a conventional oven – air fryers require far less energy to operate, and so can cost a lot less to run.

"Your average air fryer will be around one and a half, maybe two kilowatts, something similar to a kettle, whereas your average oven… would be three, maybe four kilowatts," Higgins says. But it's all relative, he adds. You're hardly going to cook your Christmas dinner in an air fryer.

Words: Leonie Mercedes


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