ingenia

MARCH 2023 ISSUE 94

3D-PRINTED STEEL BRIDGE

BOOSTING UNDERSEA BIODIVERSITY

BATTERIES' ROLE IN DECARBONISATION

DESTRUCTIVE IMPACT TESTING

Royal Academy of Engineering

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WELCOME

Engineers make incredible things happen. Last month, the spotlight turned to the four winners of this year's Queen Elizabeth Prize for Engineering (page 2). With years of research, the team significantly boosted solar panel efficiency, enabling a transformation in the adoption of solar energy across the world.

Their breakthrough highlights the determination that engineers bring to protecting people and planet from harm. With research there is also testing, such as the crash-testing of cars by Thatcham Research (page 21). A 200-millisecond crash, and highly engineered test dummies, are behind ensuring every car passenger's safety.

Bioengineers are among the professionals protecting people from disease, with many working on innovative new medical devices. Take the magnetically guided colonoscope on page 38. It is designed to make detecting diseases such as bowel cancer easier, as well as less painful for patients.

With sensors and data, engineers are protecting the health of structures, too. The 3D-printed bridge on page 26 is not only a first in how it's been made, but also in how its digital twin will predict when maintenance might be needed.

Finally, on the seabed and coastline, innovative artificial reefs built by UK startups (page 10) are nurturing vital marine ecosystems while providing physical protection to the offshore infrastructure that underpins our net zero ambition.

There's much more to dig into this issue. And as always, do get in touch at **ingenia@raeng.org.uk** or via Twitter using **#IngeniaMag** to tell us what you want to hear about.

Faith Wainwright MBE FREng
Editor-in-Chief

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Royal Academy of Engineering

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Front cover

A lightbulb shattering on impact. Engineers perform impact tests on all kind of consumer products to ensure their safety.
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Digital twins are virtual replicas of a physical object or system such as a bridge, used to monitor its operation in real time. The technology is being used to monitor the world's first 3D-printed steel bridge.

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Microelectromechanical systems (MEMS) sensors help to make many of our everyday items work.

IN BRIEF

SOLAR PANEL INNOVATORS WIN QEPRIZE

QEPrize winners (from left) Professor Martin Green, Professor Andrew Blakers, Dr Jianhua Zhao, and Dr Aihua Wang © Queen Elizabeth Prize for Engineering/Jason Alden

On 7 February, the 2023 Queen Elizabeth Prize for Engineering (QEPrize) was awarded to Professor Martin Green, Professor Andrew Blakers, Dr Aihua Wang and Dr Jianhua Zhao for their work to transform the efficiency of solar cells and dramatically reduce costs. The winners are responsible for improvements to the passivated emitter and rear cell (PERC) photovoltaic technology that have enabled solar to become the cheapest source of electricity in many countries.

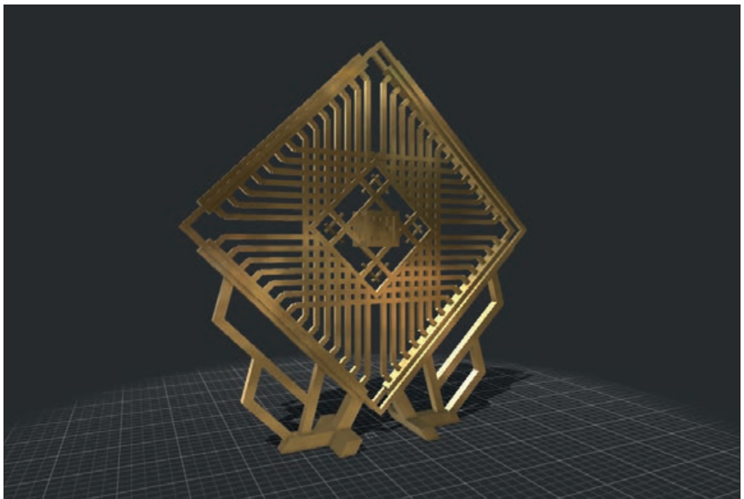
Their work significantly improved the energy conversion efficiency of commercially dominant silicon cells by improving the quality of the top and rear surface of standard silicon solar cells. PERC introduced another layer on the back surface that helped prevent recombination, and also reflected unused photons back into the silicon to generate more electrons.

During the 1980s at the University of New South Wales, Professors Green and Blakers produced solar cells with increasingly higher energy conversion efficiencies, surpassing previous records with results of up to 20% efficiency. Professor Green's lab held the global record for efficiency for 30 of the 40 years between 1983 and 2023. In work led by Drs Wang and Zhao, this eventually reached 25%.

Recognising the importance of PERC for solar energy's development, the awardees published their findings with no patent, to encourage further development and help drive down production costs to the benefit of wider society.

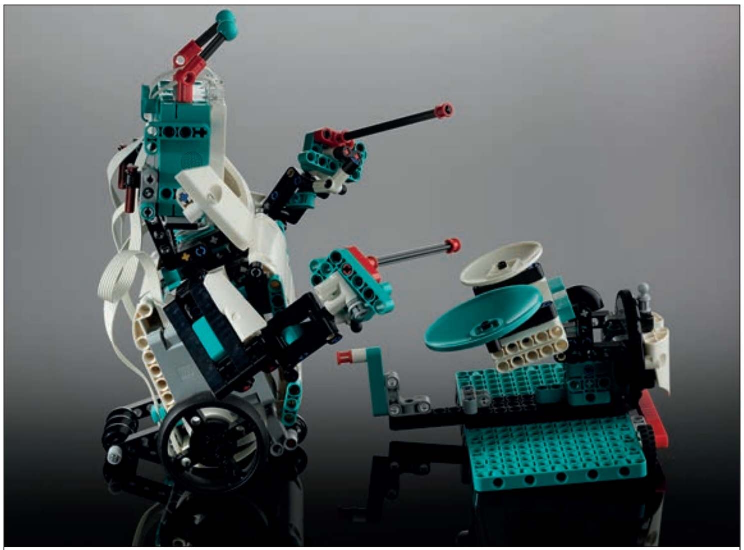
Through continued research and development, and the help of many others worldwide, the 2023 winners have significantly reduced the costs of solar panels, with the cost of solar power generation falling by over 80% in the past decade. PERC technology is now the most commercially viable and efficient silicon solar cell technology used in solar panels and large-scale electricity production, and accounts for almost 90% of the global solar cell market.

At a presentation ceremony later this year, the winners will receive £500,000 and a unique trophy, designed by the 2023 Create the Trophy winner Anja Brandl, a 24-year-old master's student from Switzerland. With 2023 marking its 10th anniversary, the now-annual QEPrize celebrates groundbreaking innovations that are of global benefit to humanity.



A 3D rendering of the winning Create the Trophy design, which is inspired by an integrated circuit

NEW ENGINEERS GALLERY AT THE SCIENCE MUSEUM



A Lego model, belonging to computer scientist and engineer Professor Larissa Suzuki, which will be displayed in the gallery
© Science Museum

In June, the Science Museum is opening a new gallery dedicated to world-changing engineering innovations and the diverse and fascinating range of people behind them, supported by the QEPrize.

The Engineers gallery will celebrate engineering heritage and showcase groundbreaking innovations, with current and past QEPrize winners featured throughout.

The gallery will host illustrated, characterful stories from more than 60 engineers working in a broad range of industries, such as farming, fashion, robotics, and medicine, shining a light on their lives, motivations, thought processes, and what they do day to day. These stories sit within four distinct sections.

'Bodies' will look at how controlled drug delivery and surgical robots place people and their bodies at the heart of precision engineering practice. In 'Lives', LED lighting and digital imaging sensors illustrate how engineers work sustainably, building enduring businesses, with a minimised ecological footprint. In 'Connections', GPS, internet and web technologies represent engineering as a connected practice, with diverse teams creating new global information and communication systems. 'Creating' looks at how engineers create products, from software to suspension bridges.

Dr Hayaatun Sillem CBE, CEO of the QEPrize and the Royal Academy of Engineering, said: "2023 marks the first decade of the QEPrize and its role in championing bold, ground-breaking engineering innovation that is of global benefit to humanity. Working with our global QEPrize Ambassador Network of early career engineers, some of whom are featured in this exhibition, we aim to inspire young people from all backgrounds, all around the world, to consider a future career in engineering."

FIRST IN-PERSON IMPLANT FOR INCONTINENCE TREATMENT

A University of Oxford spinout has implanted bioelectronic therapy to treat urinary incontinence (UI) in human patients for the first time.

Amber Therapeutics has developed Amber-UI, the first fully implantable, closed-loop bioelectrical therapy in clinical development for UI. The implant can access and target the pudendal nerve – the nerve that directly controls continence – through a novel, minimally invasive surgical procedure. The treatment can both directly regulate the urge to empty the bladder (urge incontinence or overactive bladder) and increase resistance to urine leakage caused by activities such as coughing or lifting (stress incontinence), allowing for restoration of normal bladder function.

Aidan Crawley, Amber's CEO, commented: "Reaching this first-in-human milestone in under two years demonstrates our ability to rapidly prototype new bioelectrical therapy concepts. But what is most exciting is the potential for our UI therapy to have a radical impact on clinical outcomes not only in patients with urge UI, but also for the first time in the many more patients with mixed UI for whom no single therapy is currently available."

The study is being conducted at the University Hospital Antwerp, Belgium, by Stefan De Wachter, Professor of Urology, a leading expert in pelvic floor disorders and a co-founder of Amber, in partnership with Bristol-based Bioinduction Ltd.

AIR FILTERING BACKPACK DESIGN WINS STUDENT ENGINEERING COMPETITION

Eleanor Woods with a prototype of her air filtering backpack
© Institution of Engineering and Technology

A 12-year-old from Huddersfield has won a national engineering competition with a design to filter polluted air, to help the eight million people in the UK who suffer the often-crippling effects of asthma.

The Institution of Engineering and Technology (IET) chose Eleanor Woods' 'Breathe Better Backpack' as the winner of its 'Backpack to the Future' competition. The IET teamed up with global lifestyle brand HYPE. – challenging kids to supercharge fashion with STEM and invent a backpack that helps them do incredible things. Eleanor's design – inspired by her mum's experience with asthma – featured a built-in air filter and fans, powered sustainably by solar panels and a dynamo.

Eleanor's entry impressed judges with its ability to make a positive difference to people's lives and to the planet.

Presented with her prize, a working prototype of her winning backpack, Eleanor said: "I was really shocked when I found out I'd won, I really didn't expect anything when I entered the competition! I thought of my backpack to help clean the air because some of my family and friends have asthma and hayfever and it could help them. I'm very happy the judges chose my entry as the winner. I think it's a great idea to have cleaner air anywhere you like!"

Eleanor's winning design will be displayed in HYPE.'s London Flagship Store.

The judging panel included Professor Danielle George MBE, HYPE.'s CEO and Co-Founder Bav Samani, IET's 2021 Young Woman Engineer of the Year Dr Ciara McGrath, and Mira Nameth, Founder of sustainable fashion brand Biophilica.

NEW CENTRE TO CHAMPION INCLUSIVE ENGINEERING

Queen Mary University of London has launched a new centre that aims to provide all its students studying STEM subjects with an equal opportunity to become scientists and engineers.

The Centre for Academic Inclusion in Science and Engineering (CAISE) will work across the university's Faculty for Science and Engineering to ensure that it offers an inclusive curriculum and that students are supported equally throughout their academic and career development. It will use an evidence-led, intersectional and interdisciplinary approach.

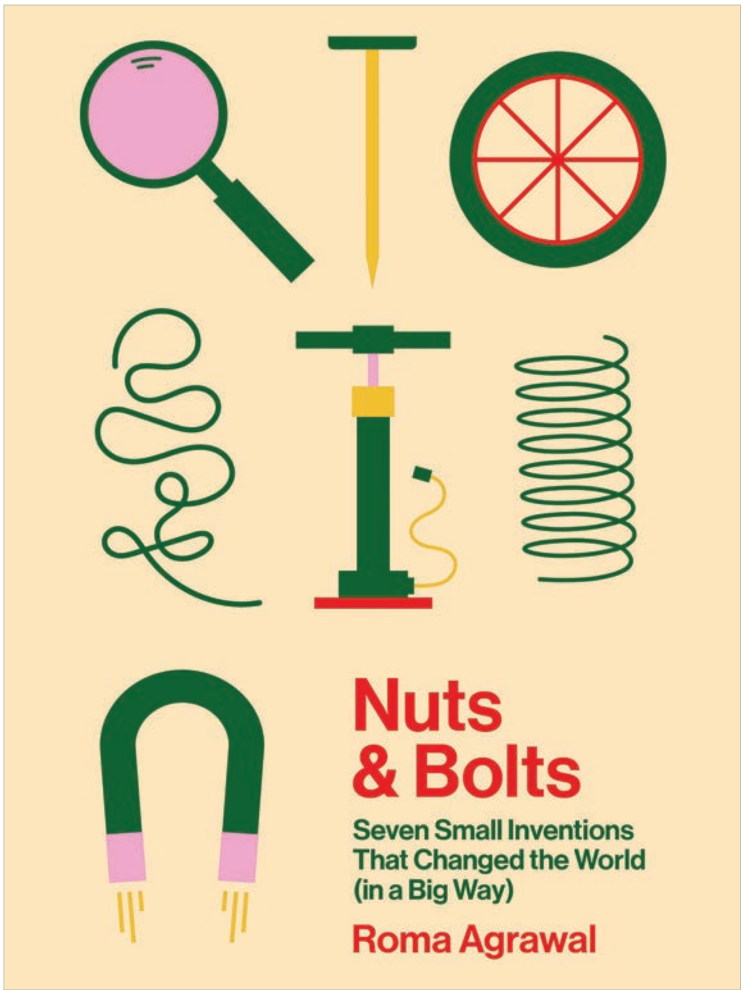
CAISE Director Dr Gabriel Cavalli said: "The focus of CAISE is to embed disciplinary literacies and practice in the curriculum, such as Thinking like a Scientist and Engineering Judgement. It will support our academics to be better and more inclusive educators.

"Data has shown, for example, that these invisible barriers, such as the use of expert jargon – or 'STEMglish' – disproportionately affects minoritised groups. We will also consider how to better support students undergoing mental health issues, as well as neurodiverse students, building on the excellent work on neurodiversity championed by the Queen Mary Academy."

© Jason Goodman/Unsplash

To read a blog from Dr Cavalli about the role of the centre, please visit **www.ingenia.org.uk**

GET INVOLVED IN ENGINEERING



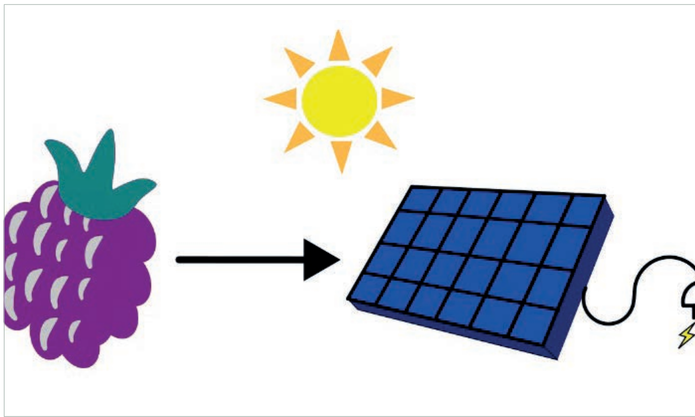
NUTS AND BOLTS: SEVEN SMALL INVENTIONS THAT CHANGED THE WORLD (IN A BIG WAY)

Award-winning structural engineer Roma Agrawal MBE HonFREng's new book looks at how seven fundamental inventions – the nail, spring, wheel, lens, magnet, string, and pump – have impacted on the most complex feats of engineering. Available to buy now.

ENGINEERING THE MODERN WORLD

April 2023
London and online

Provider of educational talks and lectures, Gresham College has three talks coming up in April looking at the challenges facing modern engineering: what is the role of nuclear power in a net zero system?; architects and engineers: making infrastructure beautiful; and the future of tall buildings. Register via the website: **www.gresham.ac.uk/watch-now/series/engineering-world**



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CAMBRIDGE FESTIVAL

17 March to 2 April 2023

The Cambridge Festival is a mix of online, on-demand and in-person events covering all aspects of the world-leading research happening in the city. Attendees have the choice of over 350 events and activities – including panel discussions, film premieres, self-guided walking tours, and interactive activities. Researchers will show you how to make a prosthetic heart valve, let you get hands on with a range of materials, and you can even make a solar cell from berries. To find out more, visit **www.festival.cam.ac.uk**

BIG BANG FAIR

21 to 23 June 2023
Birmingham NEC

Registration for this year's Big Bang Fair is now open. Providing schools with a wealth of interactive activities and STEM inspiration, students can access careers advice and meet with scientists and engineers. Visit **www.thebigbang.org.uk/the-big-bang-fair** to sign up.

HOW I GOT HERE

Q&A

ISABELLE PICKETT
CHEMICAL ENGINEERING STUDENT

A chemical engineering degree set Isabelle Pickett on a path to advocating for girls in STEM and net zero careers – and setting up her own tutoring business along the way.

WHY DID YOU BECOME INTERESTED IN SCIENCE AND ENGINEERING?

I had a physics teacher in secondary school who mentioned chemical engineering to me at a parents' evening. Her encouragement, along with how engaging her lessons were, really inspired me to pursue sciences and maths to A level, and then ultimately a degree in chemical engineering.

HOW DID YOU GET TO WHERE YOU ARE NOW?

At sixth form I studied subjects that I thought could give me the widest access to degrees that I'd be interested in. After I finished my exams, I did a Year in Industry placement with Schneider Electric to confirm that chemical engineering would be a good degree choice for me – after all, it was a five-year commitment! I then accepted an offer to study chemical engineering at the University of Bath and during my degree did a year-long placement at AstraZeneca. Outside of university, I got involved in outreach opportunities, specifically those encouraging girls to study STEM subjects and pursue careers in reaching net zero.

Most recently I have attended the One Young World conference and COP27 in Egypt, as a delegate of the Institution of Engineering and Technology and the Royal Academy of Engineering.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

Winning Engineering Student of the Year at the 2022 Engineering Talent Awards. I was proud to be recognised for the work I've put in to encourage more girls to pursue STEM careers. It has really given me the confidence to keep working towards a more inclusive and diverse engineering community.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

Working to change things for the better. I recently went to COP27 and got to see first-hand the incredible technologies engineers are working on to help us get to net zero. The best thing about being a woman in engineering is the opportunity to break down gender barriers and pave the way for future generations. As a woman in a male-dominated field you have the chance


Isabelle being interviewed by youth-led NGO, Action4Climate, during COP27 in Sharm El-Sheikh

QUICK-FIRE FACTS

Age: **24**

Qualifications: **A levels in chemistry, maths, physics, and economics, and a master's in chemical engineering (pending!)**

Biggest engineering inspiration: **Dame Caroline Haslett – a trailblazing electrical engineer and Suffragette who believed in using electrical power to emancipate women from household chores**

Most-used technology: **my laptop!**

Three words that describe you: **motivated, determined, enthusiastic**

to prove that women are just as capable as men and bring a unique perspective to the table. I have really enjoyed being able to connect with other women who are considering entering the field and trying to make a positive impact on diversity and inclusion.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

No day is the same! I am currently completing my master's design project, for which I am working in a team to design a carbon capture plant. A typical day now involves researching carbon capture technology and assessing its economic feasibility, then meeting up with my team to further develop the design of the plant. I also run a tutoring company so after my university work is done, I often have meetings with tutors and parents to check up on progress and brainstorm ideas for ways we can improve.

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

Go for it and believe in yourself. Young women engineers are often dissuaded from a career in engineering, but it is so rewarding and really gives you an opportunity to inspire the next generation to feel confident pursuing the career. It's so important to seek out role models and mentors. Having a good mentor has been really important to my development as an engineer – it is great to have support from someone you aspire to be like, and those connections will really help you with career decisions.

WHAT'S NEXT FOR YOU?

I'm hoping to complete my master's this summer and then to use my degree to make a positive impact. I'd love to engage in more outreach activities and empower women students to pursue their passion in STEM. I believe that it is crucial to create a more diverse and inclusive environment in the field of engineering, and I want to be a part of the movement to make that happen. I would love to ultimately use my career to contribute towards achieving a net zero future and solving the issue of climate change. I believe that engineers will play a pivotal role in developing sustainable solutions that will lead us to a cleaner and greener future.

OPINION

HOW CAN LEARNINGS FROM COVID-19 ACCELERATE UK TECHNOLOGY DEVELOPMENT?

In 2020, at the height of the COVID-19 pandemic, engineers from across the profession worked together to produce ventilators for hospitals across the UK through a consortium that became known as the VentilatorChallenge UK (VCUK). Three years on, there has been a determination not to lose the learning from this project and many involved have continued to pursue this template. Members of the team, Ian Quest, who led the Programme Management Office team during VCUK, and Dick Elsy CBE FREng, CEO of the High Value Manufacturing (HVM) Catapult, reflect on how we can take this further.

Ian Quest

Dick Elsy CBE FREng © thisisjude.uk

We near the third anniversary of a feat of engineering that occurred at the height of the COVID-19 pandemic. In early 2020, with the UK facing an anticipated shortage of intensive care ventilators and no ability to rapidly procure them, the government asked industry if it could repurpose, to manufacture thousands urgently. There was no shortage of volunteers but no coherent plan, leaving private enterprise to make its own arrangements.

The HVM Catapult, Europe's largest advanced manufacturing research institution, stepped in to pull a consortium together. In just four weeks, after being introduced to a prototype unit from anaesthesia equipment manufacturer Penlon, the consortium (VCUK) had built five factories and sourced 11 million parts. In the next 12 weeks it made over 11,000 intensive care ventilators, with production peaking at 400 a day ('All hands to the pumps', *Ingenia* 86).

The approach required collaboration, empowerment, the use of open data and radical digital tools: it was a template for the future.

As well as the many specific things I learned from both the project and the people, I took away an elevated sense of what's possible, condensing a two to three year 'normal' timeline into three months. We asked: why we can't do this every day, especially at a time when developing and scaling new technologies is so critical?

Obviously, there was a very clear and compelling purpose that everyone got behind – and the extraordinary circumstances enabled extraordinary creativity. The importance of succeeding also meant that a 'nothing is impossible' culture quickly grew across the team, which asked 'how' not 'if' something could be done.

Another key ingredient was the group's expertise (aided of course by furlough) led by an awareness of gaps and individual limitations and a willingness to source the right expert. These individuals were then trusted to make decisions and deliver with little hierarchy.

We were supported by a truly democratised approach to data and information, where all parts of the team could use well-maintained, accurate data to make decisions. This was delivered through on-the-ground data management and a suite of rapidly created 'pop-up' tools. Without this, the delegated decision-making necessary to meet the pace would not have been possible.

Having caught up recently with several fellow collaborators, it's clear that these learnings have impacted all the organisations involved. A member of McLaren's F1 team cited more focused reporting and greater empowerment. Penlon report a shift in mindset to 'how' from 'if'. At Airbus, clearer and more compelling goals with more delegated responsibility have helped drive pace. Ford ran a special vehicle project based on these learnings and delivered a prototype in 1/3 normal time. At Quick Release there is a new comfort with sharing initially imperfect programme information much earlier with a view to getting the data right faster.

Alongside these successes, there are still frustrations that these learnings are not being absorbed faster across industry and with an even greater impact.

An obvious difference is making goals compelling to everyone; few challenges will be as urgent or relatable as COVID-19. Collaborators have also reported difficulty in dedicating and empowering the right resources, which often requires them to pull people from key roles elsewhere, breaking established structures and hierarchies to form a cohesive team. Truly democratised sharing of usable, accurate and timely information is then needed to empower the team, and legacy tools and habits often don't support elevated pace. Lastly there is a significant challenge in proliferating a 'nothing is impossible' mindset without the lived experience. VCUK had an imposed timeline, so we had to suspend disbelief and ask 'how?'. Asking teams to slash project timelines on faith when the impact is less direct is more difficult.

So, how do we need to change?

- Frame the challenge. Goals must be clear, compelling and relatable. Ask how they will impact the world, your customers, the company, and the team. Break longer challenges into smaller, clearer goals. Listen to individuals' motivations and keep the message alive in regular communications.
- Break structures and hierarchies and dedicate the right people. Old structures come with old habits, so create a fresh diverse team chosen for the specific needs of the goal. Consider secondees from elsewhere to get the right mix. Be bold and – if you need to – shorten the timeline or adjust the goal before compromising on people.
- Don't be tied to old tools; do nurture your data. Legacy tools and systems are often slow and oversized so enable some freedom, but don't lose grip on your data. Focus resource and energy on making data timely and accurate and then provide the support, visualisations and reports to allow quick and informed decision-making.
- Build critical mass of a 'nothing is impossible' mindset. Include people with lived experience and take time ahead of starting to share those experiences and stories with everyone and ensure there is belief your goals can be met.
- Unreasonable goals. If we want to achieve unprecedented results and foster a 'nothing is impossible' mindset, then – almost by definition – we can't follow a traditional 'realistic' plan. If we plan based on what we know now, it will inhibit us pushing the envelope.

Project directors can only implement change if there is a shift in how projects are funded, how they are led, and the way we build the teams and environments to deliver them.

When making decisions, funding bodies should look more closely at the team and demand less by way of detailed plans. How we build teams needs to be more sophisticated, looking beyond skillset to mindset and personality and avoiding defaulting to old or established hierarchies. Spending informal time together and having regular team-wide communications will help nurture a new dynamic. Support roles such as coaching, data curation and process support should be planned for, so that emergent issues can be jumped on when they inevitably hit.

There are many successful examples of centres of excellence, such as those within the HVM Catapult and the APC (Advanced Propulsion Centre), which have created environments where collaboration thrives. Supporting more national activity like this and nurturing and driving success in these projects would develop more people with the lived experience and strong ties to a broader group of people.

Lastly, in support of compelling goals, it would be helpful to see a clearer steer on UK plans for technology, such as a cascaded strategy for net zero. With this, each technology area gets clearer high-level goals from which to derive competitions and specific project goals that are tied to crucial and relatable outcomes.

The VCUK legacy has been profound for many of those involved. Most have taken something back to their core role and effort has gone into identifying and sharing the key ingredients for success. But there is much that only lived experience will deliver and wherever there is an ambition for rapid delivery, we should seek to apply all these lessons collectively and infect a growing group of engineers with a belief in what's really possible.

BIOGRAPHIES

Ian Quest is Director of Consulting at Quick Release, specialising in de-risking and accelerating engineering programmes. He led the programme and data management for the Penlon consortium of VCUK. He now focuses on helping clients get key technologies to market faster.

Dick Elsy CBE FREng is Chair of AB Dynamics plc and is on the board of AWE plc. He takes a keen interest in innovation at a national level and chairs the Faraday Battery Challenge Advisory board and the UKRI STFC Business and Industry Partnerships Board.

HOW ARTIFICIAL REEFS BOOST BIODIVERSITY

Artificial reef structures ready to be placed at the coastline to become a home for marine life, while protecting key structures © ARC Marine

Did you know?

- Coral reef structures can buffer shorelines against 97% of the energy from waves, storms and floods
- Marine life can make a home in places as diverse as bamboo structures, sunken warships and old train carriages
- Engineers are investigating new materials for artificial reefs, to minimise carbon emissions and avoid plastics

Coral reefs and coastlines face growing challenges from climate change. Beverley D'Silva spoke to teams from two UK startups developing novel solutions to protect and renew marine ecosystems.

Coral reefs are among the most diverse and valuable ecosystems on Earth. And yet, they are vulnerable to mass bleaching due to warming seas and ocean acidification, as well as pollution, overfishing and destructive fishing practices. Once living coral is weakened or broken, sea storms and changing water chemistry erode the calcium carbonate skeletons on which reef life attaches itself. Both tropical and cold-water coral reefs have been affected globally.

Alongside reef destruction is coastal erosion. This happens naturally, but climate change and human interference have resulted in increasingly retreating coastlines and beaches. Coral reef structures can buffer shorelines against 97% of the energy from waves, storms and floods, to help prevent erosion and damage to property and life. Reef conservation, research and restoration is of paramount importance.

As a response to these crises, engineers are creating artificial reef structures (ARS), which are deliberately placed in the sea to reproduce some aspects of a natural reef.

BAMBOO, WARSHIPS AND OLD TYRES

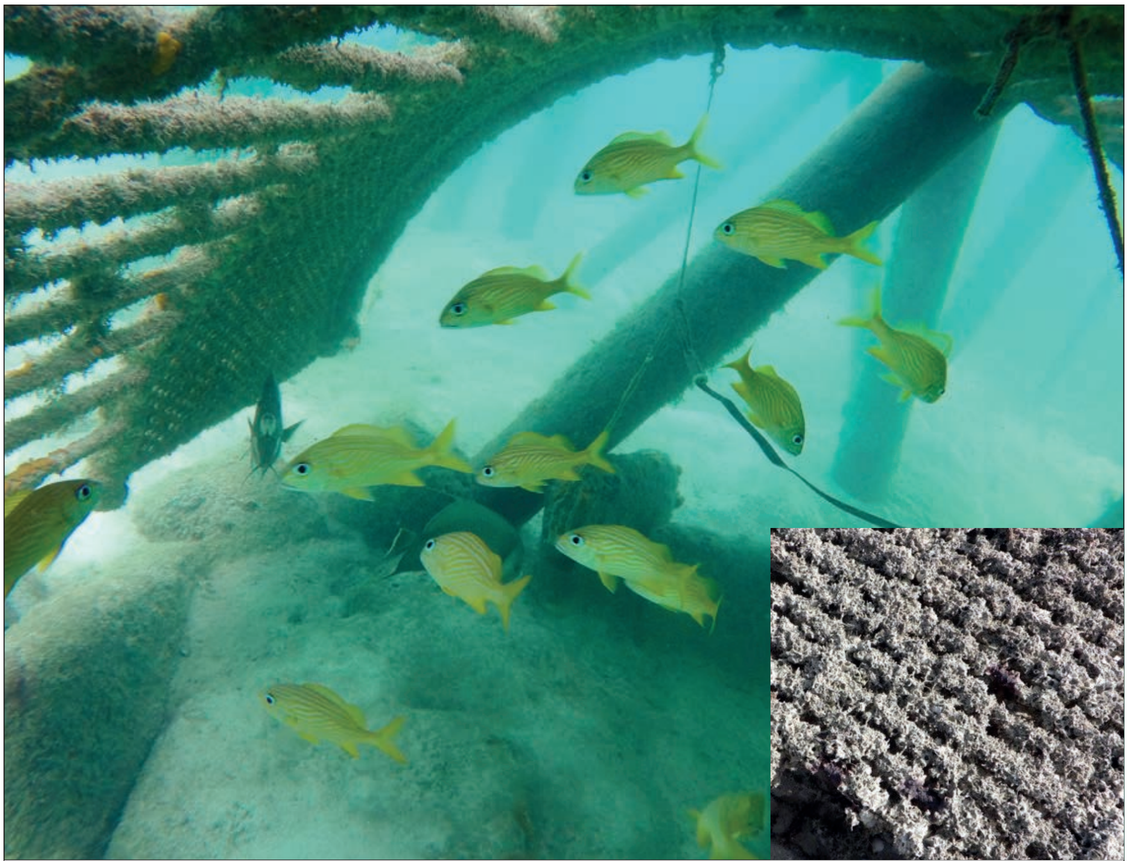
ARS are not new. The first intentional structures date back to at least 18th-century Japan, when structures made from bamboo and leaves were sunk to increase fish yield and for algaculture. Later, ships sunk during the First World War and Second World War became 'accidental', but efficient, artificial reefs. As it transpired, thick, heavy-gauge steel, sufficiently corroded by seawater, could provide a suitable texture for coral attachment. Old boats, train carriages and cars, when sunk, were also considered workable solutions – if they were stable, non-toxic and provided a suitable surface for marine organisms to latch on to.

However, the business of devising ARS has not been without its disasters. Take the 1970s' Osborne reef project in Florida. This involved dumping a mass of two million old tyres, linked with metal clips, onto the seabed, to bolster existing reefs while disposing of old tyres from Goodyear and landfill. While it may not sound like it by today's standards, it was created with the best intentions: an idea from a non-profit group, endorsed by the US Army Corps of Engineers and following similar projects in the northeast and Gulf of Mexico. But it soon began to fail. The clips connecting the tyres corroded and parts broke loose, damaging nearby natural reefs. Strong tides, hurricanes and tropical storms moved tyres thousands of miles. By the 2000s, the project was considered an environmental disaster. Studies showed it was leaching toxic chemicals – and almost no fish were living in the area. A cleanup operation was launched, but even as of 2019, only 250,000 tyres had been collected.

Thankfully, the tide, and awareness, is turning against such eco-malpractice. The focus today has shifted significantly to ensuring ARS are environmentally friendly, and preserve and encourage biodiversity.

AN ELECTRIC SOLUTION

CCell is a UK set-up, whose motto is 'building reefs to combat coastal erosion in harmony with nature'. Dr Will Bateman, its CEO and Founder, is a civil and environmental engineer, whose PhD from Imperial College London was on modelling extreme ocean waves. Back in 2015, Bateman, a keen diver, was in Playa del Carmen in Mexico, when he noticed sandbags outside a beachside hotel that was part of a large international chain. "They were trying to stop the waves, which were coming in close to the



One of CCell's artificial reefs in action. Inset: a close-up of one of their reefs, populated with barnacles © CCell

hotel's foundations," he says. He later discovered that about 30 to 50 metres of the beach had been lost between 2017 and 2019.

Coastal erosion is not new, he asserts. "You could argue the White Cliffs of Dover are white owing to perpetual coastal erosion." However, he says because of climate change, many areas have seen long-term wave characteristics – also called 'wave climate' – growing more intense over the past 80 years. He flags a 2019 study on wave climate, showing that global wave power increased by 0.41% each year. "Accumulating over 20 to 30 years, it has quite an impact," he says. Furthermore, "studies show a noticeable shift in the past 10 years, and erosion rates have become far more aggressive."

Bateman switched CCell's focus to combating coastal erosion. "Coral reefs are natural barriers to erosion, causing waves to break at sea," he says. The company's goal became one of replicating natural reefs. In doing so, they would create a habitat for marine life, while returning beaches to their former states.

Conventional solutions to coastal erosion include 'hard' solutions, which have not changed since Roman times, involving taking "the largest rocks or concrete units you can lift" and piling these up along the shore. Another option, beach replenishment, "is a sticking plaster approach that involves pumping sand back onto the beach only to watch it wash away again", says Bateman. More recent 'soft' solutions include large sandbags that break down after three to five years, causing further damage with plastic pollution.

CCell's challenge was to create a reef that could be efficiently made and easy to transport. The company devised a system that could be installed with just two workers, without the need for large boats or cranes. The lightweight, modular steel units are typically 2.5 metres long and up to 3 metres high. They can be stacked for transport "like supermarket trolleys" and the design adjusted for water depth. "The goal is to create a submerged unit that affects the waves at the surface, akin to most coral reefs." This means the reefs themselves don't have to resist the high loads that arise in the surface of the wave, especially breaking waves.

The engineers use seawater electrolysis to grow the rock on the steel reefs, an approach known as an electrified reef. To do this, a safe, low-voltage current is applied to the reef, controlled via a digital management system. As the current flows, oxygen, which is beneficial for marine life, is produced at the anode. Meanwhile, the pH rises at the cathode (the main structure). This precipitates minerals dissolved in seawater to form rock, which provides the structure with the necessary bulk to affect the wave climate.

"The rock, mainly calcium carbonate and magnesium hydroxide, grows at about 18 millimetres per year and will heal if damaged," says Bateman. He describes it as "the perfect medium on which to put oysters or corals." The company is also working with marine biologists to plant carbon-capturing, wildlife-supporting seagrass in and around the reef structures.

What evidence have they seen that ARS can support biodiversity and marine life? CCell is waiting for results from four pilot installations at global sites. The team is monitoring a beach in Telchac, Mexico, where "visually there's been an improvement of two metres…. We've also been blown away by the increase of fish numbers."

A CCell reef costs $1,000 to $5,000 per metre, depending on the site. The company has won contracts with hotels and high-end property owners, and partnerships with marine engineering companies in Mexico, India and Europe.

A lobster sheltering in the passageway of one of ARC Marine's reef cubes® © ARC Marine

These first pilots at hotel beaches are just the beginning: one of CCell's next projects involves building an artificial reef at a £100 million yacht marina on the Isle of Man. "CCell has been commissioned to ensure the development is as ecologically sensitive as possible," a spokesperson for the firm Ramsay Marina Ltd told BBC News. It is trialling the technology at the island's Douglas Harbour to provide scour protection for the marina's walls, all the while giving the ecosystem a boost.

LOOKING TO THE NORTH SEA

Elsewhere around the shores of the UK, a very different type of artificial reef is being explored. Like CCell's structures, they are being used for coastal defence, although they resemble the conventional 'hard' solutions. But they have another vital application – to protect offshore structures crucial for a net zero future, from wind turbine foundations to undersea power cables.

The precedent for these cold-water ARS was set by the Loch Linnhe Reef project in Scotland. The seven-year multidisciplinary project was Europe's largest ARS when it began in 2000. "ARS can enhance local-scale biodiversity, but only where they offer a new habitat for marine life," says Dr Tom Wilding, a seafloor ecologist who worked on the project. He says this is seen, to some extent, on the Loch Linnhe Artificial Reef, "as it is located over a range of sediment types."

The main reef complex at Loch Linnhe consists of five groups of six individual reef modules deployed in water between 12 and 30 metres deep. Each reef module consists of 4,000 concrete blocks. Along with obtaining the necessary licences and permissions, primarily from Marine Scotland, one of the biggest challenges for the project was determining the optimal manufacturing and construction approach. After settling on concrete blocks, the reef cost £1 million, including licensing, research costs, manufacturing ,and installation.

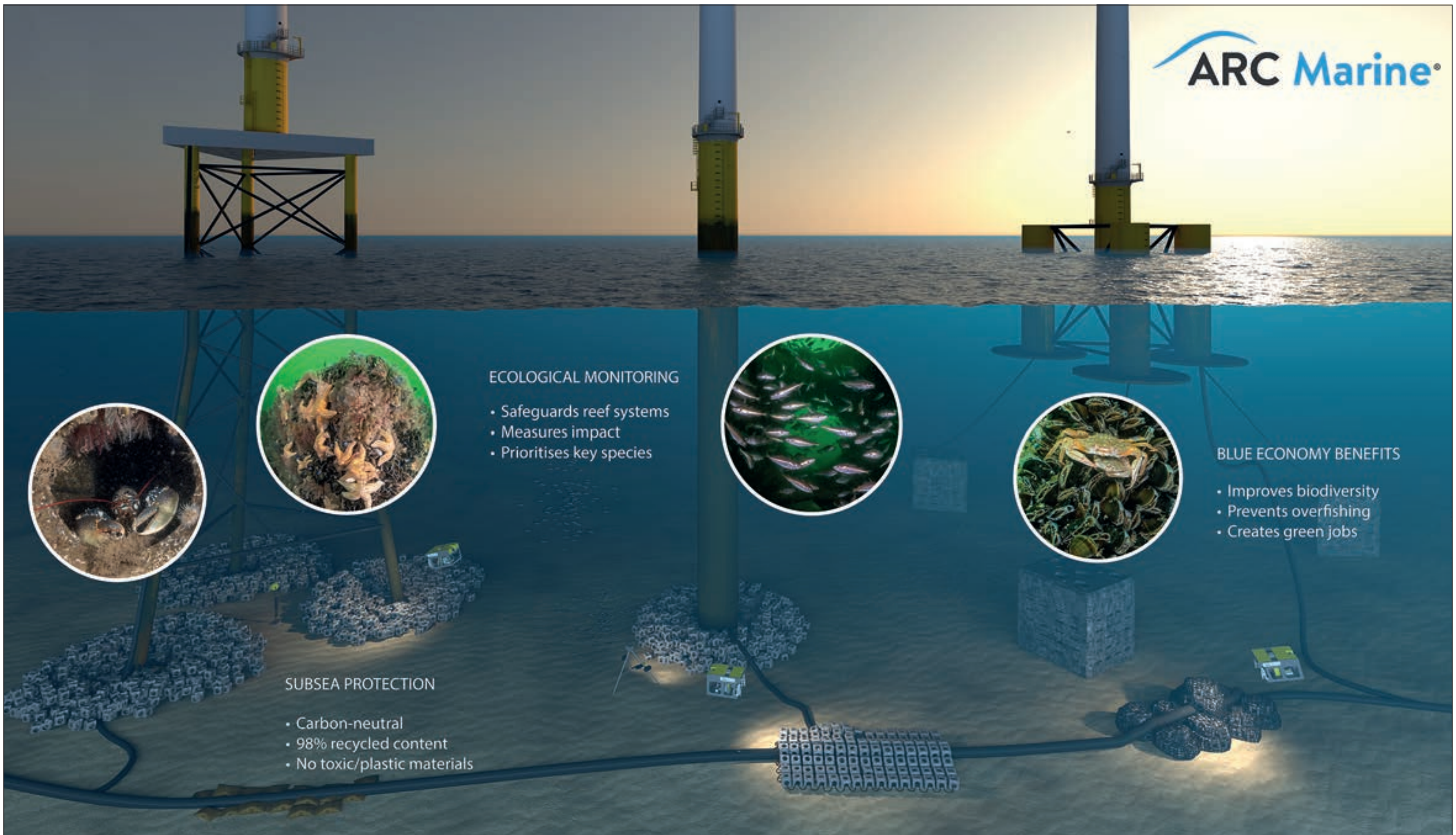
However, concrete is not known for its environmental credentials. In the hopes of finding a greener alternative, ARC Marine was launched in 2015 by CEO and Founder Tom Birbeck. Birbeck's background is not in engineering, but documentary research. A keen diver, like Bateman, he was looking for subjects to film. On one dive he was shocked to witness "shoddy concrete being used to protect subsea assets and harbour walls. I thought we could make much better concrete for reef material."

Birbeck set up ARC Marine, in Torquay, Devon. Collaborating with the universities of Plymouth and Exeter, the team created reef cubes®. Made from Marine Crete, an alkali-activated low-carbon alternative to concrete based on ordinary Portland cement, the award-winning cubes each weigh about 5.5 tonnes and can be placed from the high intertidal mark to the subsea, depending on requirements. They are a low-carbon, plastic-free solution for coastal defence, subsea protection and marine habitat restoration.

"Rock armour requires a lot of carbon to transport, and produces a lot of waste," says Birbeck. He explains that it is blasted from Scandinavian quarries using explosives – also necessitating transport over large distances. "By contrast, our bespoke units can be made close to site and are engineered and designed to what's needed."

Promoting biodiversity was always a priority for ARC. 'The main idea to incorporate into the design of an effective artificial reef is the complexity of the habitat,' says Sam Hickling, the company's Chief Scientific Officer. This complexity is increased by incorporating features such as grooves, pits, overhangs, ledges, and holes. Features are selected based on evidence for their ecological benefits, before being incorporated into ARC's designs. "Our Marine Crete reef cubes® provide a wide variety of habitat niches, as opposed to reefs that use standard smooth concrete."

Design features in hard structures can be as basic as "a



Different types of artificial reefs can be used to protect a variety of offshore infrastructure, from mattresses for subsea power cables, to blocks for wind turbine monopiles © ARC Marine

central spherical chamber with a passageway on each side". According to Hickling, studies show these increase the presence of organisms called suspension feeders, which filter out organic carbon and nutrient material from the plankton and particulate matter in the water. This may be because of the increased surface area for attachment it offers, or possibly shelter from predators. "It increases the ecosystem's biodiversity and abundance," he explains.

NOT YOUR ORDINARY PORTLAND CEMENT

Harrison Short is ARC's Project Engineer, looking at the operational aspects of deploying its unique solutions. When he joined the company, six months ago, it had already invented its Marine Crete, a secret mix with a compressive strength that achieves between 30 and 50 Newton compressive strength after 28 days – comparable to conventional concrete mixtures used in structural engineering. Short explains: "It is also more impervious to seawater than conventional concrete mixes using Portland cement and is therefore well suited for use in the marine environment."

A lifecycle analysis of the cubes by an independent expert at the University of Plymouth calculated a 91% reduction in carbon emissions, compared to if they had been made from concrete containing ordinary Portland cement. "The analysis is based on the production of 1 tonne of concrete, in comparison with conventional Portland cement-based concretes," explains Short. "This emissions value was based on a cradle-to-gate analysis of the product, including raw material production, transport and our entire manufacturing process – up until the point where the cast concrete unit leaves our yard.

"The 91% figure can vary slightly depending on the locality of the aggregates used in the mix. However, we always use locally sourced materials wherever possible. We're working on our carbon neutral and carbon negative concrete ranges, including extra carbon-sink material incorporated into our mix to offset the production process." ARC Marine plans to have an updated analysis of Marine Crete undertaken in the next year or two, with the aim of proving carbon neutrality.

The company has installed more than 1,200 units in the UK and Europe, with another 6,000 units to come this year. Birbeck says: "We can construct reef cubes® en masse, but we can't easily install them en masse. That's our next challenge. We're working out how we can integrate them into offshore construction vessels." The company has an ongoing two-year project looking at exactly this.

PROTECTING GREEN ENERGY SOURCES

Beyond coastal defence, ARC's other clients include "anyone who puts a pipe or a cable in the seabed". For instance, offshore wind power is a mainstay of the EU's goal to be climate-neutral by 2050. The bloc has set a target for an installed capacity of 300 GW of offshore wind by 2050, while the UK aims to achieve 50 GW by 2030. Naturally, investment is flooding into offshore wind, with an estimated £60 billion going into offshore wind farm energy across the UK in the next five years.

As such, specialist structures are needed to protect subsea assets from harsh marine conditions and tidal scour – erosion at the seabed – which can damage subsea power cables and wind turbine foundations. Traditional equipment to protect subsea assets have high embodied CO_2 emissions, damage the marine environment and shed plastics. Due in part to their plastic content, these structures have a limited lifespan and legislation requires them to be removed after a certain time. When removed, ecosystems that have grown around them are destroyed too.

ARC Marine products contain no plastic and are marine friendly, falling in line with rigorous Dutch leachate standards, meaning they can be left in place so the ecosystem can continue to thrive. Its product Marine Matt is used as scour protection and to protect subsea power cables on the seafloor. It is comparable to a conventional concrete mattress containing polypropylene rope, except it contains zero-plastic rope, instead. "So, if there is decommissioning, you don't risk leaving plastics in situ," adds Hickling.

Surprisingly, offshore oil and gas platforms can make bountiful marine habits. Rigs, in place for decades, can be colonised by corals, with fish, starfish and mussels thriving in and around the steel pylons. Once a well is drained of fossil fuels and considered defunct, companies can seal it and simply remove the rig's upper section, instead of removing the entire platform. Clearly, this benefits companies, with the potential to save millions in decommissioning costs – but some argue that leaving these structures, and their associated ecosystems, in place is better for biodiversity, too. In the Gulf of Mexico, the US programme Rig to Reefs has turned 532 oil and gas platforms into artificial reefs. Closer to home, UK researchers are planning to investigate the effect of oil rigs on sea life in the North Sea, to determine whether this approach is feasible.

ARC is inspired by the Hollandse Kust (West) offshore wind farm, 28 miles off the east coast of the Netherlands and due to be fully operational in 2023. It's the world's first offshore wind farm to make nature-inclusive design essential in a wind farm development. "If you look at their scoring criteria for the tender process, over half was on how [developers have] integrated nature-inclusive design to enhance ecosystems," says Hickling. "Our hope is we can integrate or transfer that over to the UK."

Just like biodiversity net gain on land (see 'Engineering biodiversity', *Ingenia* 91), legislation is changing for marine net gain: whatever you do in an offshore and coastal construction environment must improve the environment. When ARC launched, says Birbeck, they were "banging on people's doors" to be heard. In the past two years there's been a sea change (to excuse the pun). The world has opened up to the idea of ARS. Birbeck says: "We've raised £2.5 million in equity funding and will raise a further £5 million next year. Our turnover is increasing 100% year on year. So, it's going well."

THE IDEAL ARTIFICIAL REEF

According to Dr Will Bateman of CCell: "A good reef is one that as closely as possible mimics natural reefs (coral or oyster reefs). CCell's reefs are designed to attenuate ocean waves and promote marine life, with our focus toward the creation of robust structures formed from natural minerals found in seawater on which corals, oysters and fish can thrive." He adds: "A bad reef is anything made from unnatural materials."

Sam Hickling of ARC Marine says: "The shape and surface texture of concrete appears to be the most decisive factor. We prefer to use materials that are low carbon so we use an alkali-activated material, which doesn't appear to have any negative effects on the results after a year. It seems a shame to build artificial reefs out of anything with cement-based concrete because the carbon footprint would negate the biodiversity benefits somewhat."

BIOGRAPHIES

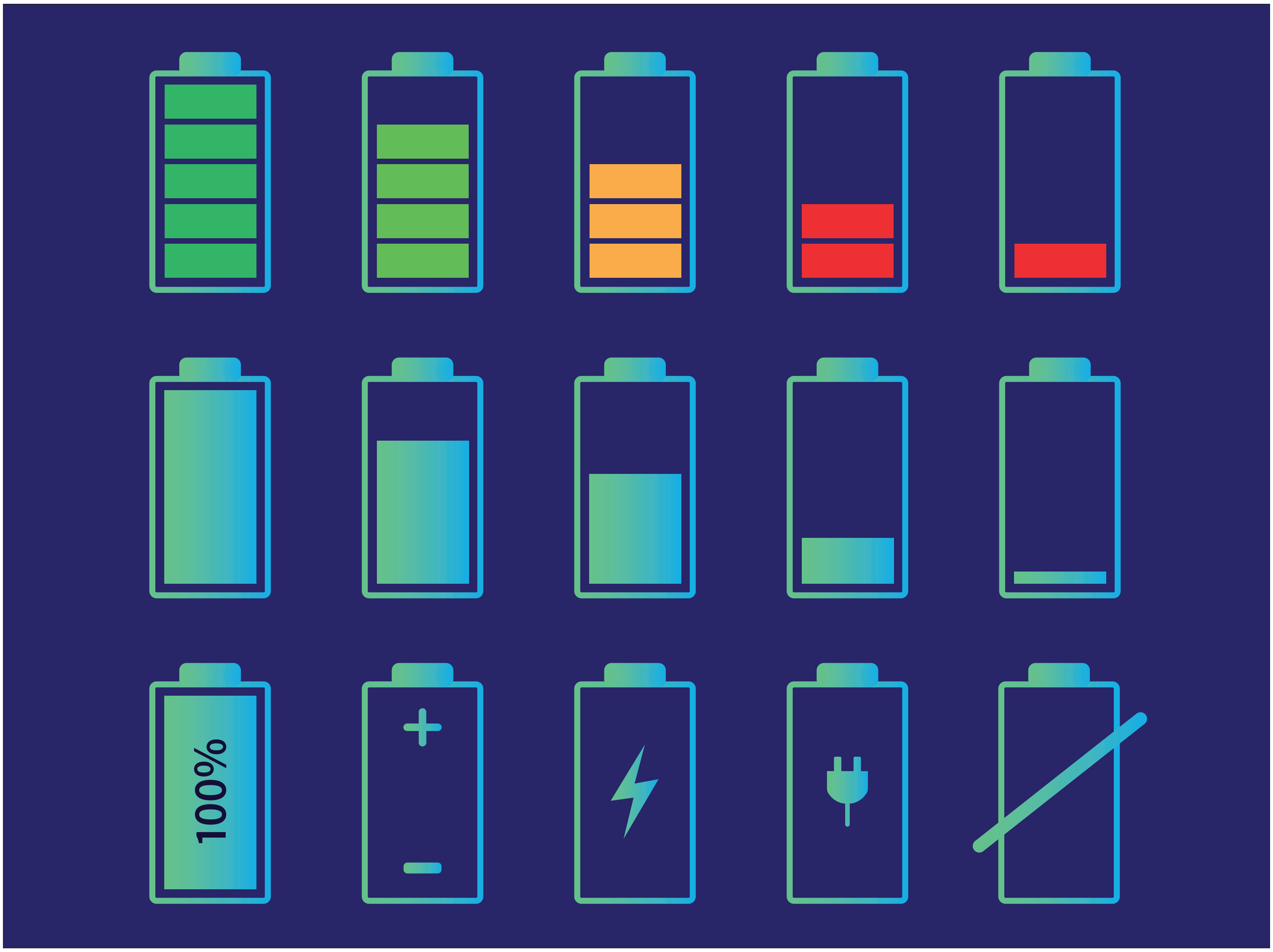
Dr Will Bateman has a PhD in extreme ocean waves from Imperial College London and over 25 years of industrial experience for RMS and Lloyd's Register. In 2012, he started working on the technologies that now form CCell.

Dr Tom Wilding, Senior Lecturer at the Scottish Association for Marine Science, is a marine ecologist, leading projects on underwater image analysis and investigating eDNA to evaluate change in the marine environment.

Tom Birbeck founded ARC Marine in 2015 with a determination to repair the world's damaged marine ecosystems. He has experience in commercial diving, aquaculture and sustainable fishing.

Sam Hickling is the Chief Scientific Officer at ARC Marine. His background is in zoology and oceanography. His favourite work activity is filming marine life with the company's BlueROV2 and ROV pilot James Murphy.

Harrison Short is an engineer with experience in marine, civil and coastal engineering looking to develop artificial reefs across the globe with ARC Marine's solutions.



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POWERING THE PURSUIT OF NET ZERO

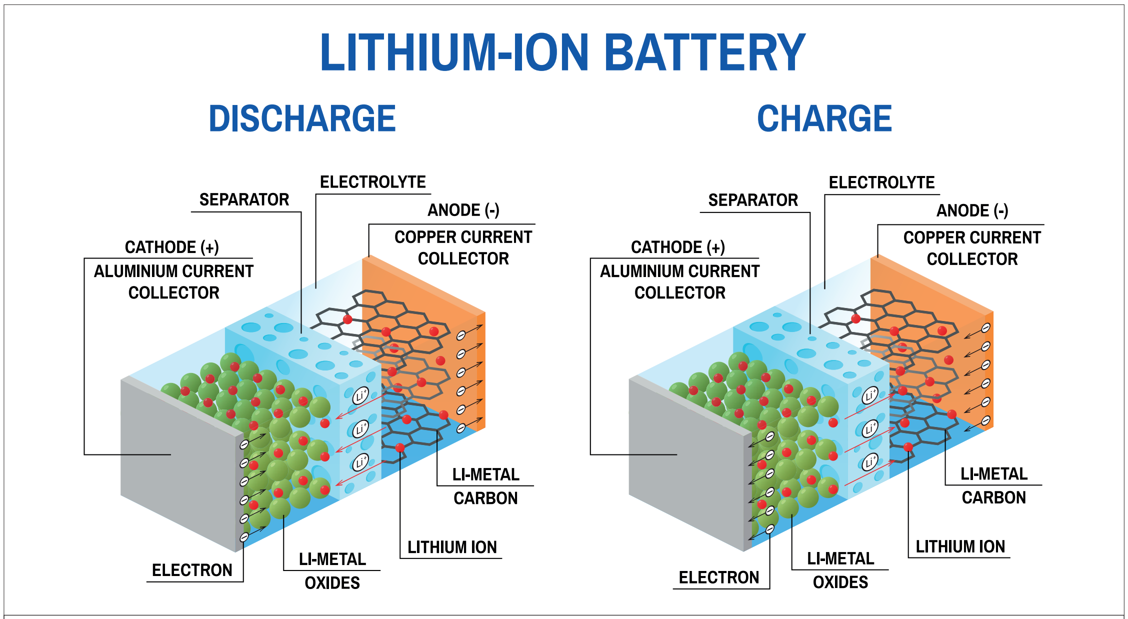
Batteries have transformed the world and will be crucial to the UK's decarbonisation ambitions. Professor Paul R Shearing, Royal Academy of Engineering Chair in Battery Emerging Technologies, University College London, looks at the challenges facing Li-ion batteries and shares how the next generation of battery technologies are being developed.

Did you know?

- Li-ion batteries are used in almost all your rechargeable gadgets
- It is expected that more than 1 TWh (Terrawatt-hour) of batteries will be manufactured in 2023 – enough to power more than 14 million electric vehicles or over 80 billion smartphones
- The Li-ion battery stores almost 10 times the amount of energy per unit weight compared to lead-acid batteries

Lithium-ion (Li-ion) batteries are one of the modern world's most transformative technologies. These are the types of rechargeable batteries you might have in your smartphone, laptop or games console. In the 20th century they revolutionised mobile computing and consumer electronics, and now promise to have even more significant impact. From decarbonising road transport to electrifying flight, batteries that range from tiny cells to power implanted devices to very large grid-scale storage will be used in a vast array of applications and will be a cornerstone in achieving net zero.

Battery is the generic term for the storage unit consisting of cells, the electrochemical units that convert chemical energy to electrical energy. In the simplest form, cells are assembled from three components: a positive electrode, a negative electrode and an electrolyte. Batteries are generally categorised as primary (non-rechargeable) and secondary (rechargeable) cells. When a Li-ion battery is charging, lithium ions from the positive electrode move through the electrolyte (generally an ionically conducting liquid) to the negative electrode. When the battery supplies power, lithium ions move back to the positive electrode. In both cases, electrons flow around an external circuit to balance the charge. The electrolyte conducts Li+ ions, but is an electrical insulator (it does not conduct electrons) so electric current doesn't flow freely through it, and alongside a physical separator material, it prevents the cell from short-circuiting. A rechargeable battery's ability to undergo reversible charge and discharge cycling over hundreds or thousands of cycles without substantial degradation is a critical indicator of its performance.



A schematic diagram showing the operation of Li-ion batteries during charge and discharge. During charge, the Li-ions move through the electrolyte from the positive to the negative electrode, and during discharge this process is reversed © Alamy

Li-ion batteries have achieved market dominance thanks to their high energy density (the amount of energy they provide), which is determined by the capacity of the constituent materials and the voltage during discharge. Practical energy density can be reported by unit weight (gravimetric energy density) or volume (volumetric energy density). Both of these must also consider the other components in the cell, for example the packaging, separator material, current collectors, and safety hardware, which all add extra weight or volume, therefore reducing the overall energy density at cell level.

State-of-the-art Li-ion batteries used in cars typically achieve about 250 Wh/kg (watt-hours per kilogram) and 700 Wh/l (per litre). The range covered depends on the make and model of car. For example, the Nissan Leaf – the UK's best-selling electric vehicle (EV) at the end of 2020 – is expected to travel 168 miles (270 kilometres) with a 39 kWh battery. However, with increasing demand for advanced batteries in more and more applications, researchers across the world have been searching for ways to improve energy density in Li-ion batteries and in the development of next-generation batteries.

DEVELOPING THE LI-ION BATTERY

Chemist Gilbert N Lewis first identified the opportunity to exploit lithium as an electrode in an electrochemical cell more than a century ago. Lithium is the lowest density metal and also has the lowest standard reduction potential. This combination makes it an ideal candidate for a lightweight battery. However, development of the Li-ion battery didn't begin in earnest until the 1970s. In 2019, US physicist Professor John Goodenough, British-US chemist Professor Stanley Whittingham and Japanese chemist Professor Akira Yoshino were awarded the Nobel Prize in Chemistry for their collective achievements that led to the development of Li-ion batteries in the 70s and 80s.

Li-ion batteries were commercialised in the early 1990s, and since then there have been improvements in safety, cost and performance. Development of cathode chemistries has provided more sustainable options (primarily a reduction in the use of cobalt); improvements in electrode formulation and cell design have enhanced practical energy density; and manufacturing scale up and automation have substantially reduced costs.

The cost advantages in battery manufacturing have led to the establishment of many 'gigafactories' (generally considered to be a battery production facility capable of >1GWh of annual output). These cost reductions are the result of an increase in highly automated manufacturing processes and standardised form factors for cylindrical, pouch and prismatic cells. As understanding and scrutiny of batteries' lifecycles increase, the need to significantly improve the 'embedded carbon' in battery manufacture to minimise its environmental impact also grows. This can be achieved through areas such responsible materials supply and recycling, reduction of process energy use and improvements to manufacturing yield. In the EV sector, the lifecycle assessment (LCA) of a vehicle is also naturally connected with the supply of electricity, and simultaneous decarbonisation of electricity supply is required to maximise environmental benefit.

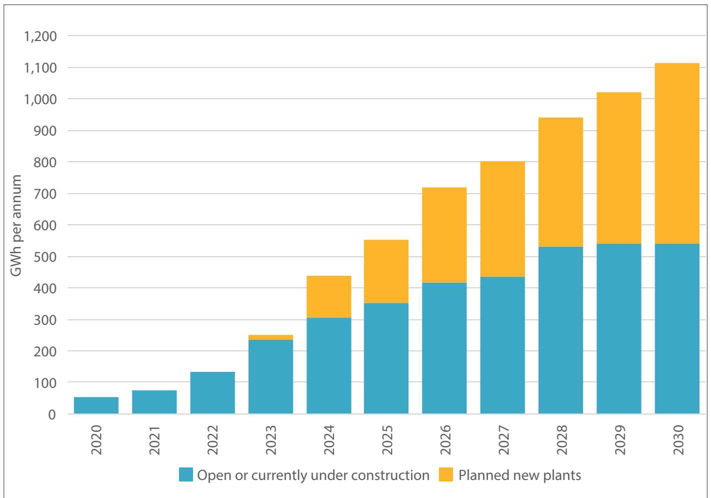
ADDRESSING CHALLENGES

Despite progress in Li-ion battery design, there is still room for improvement. There is also substantial consumer demand for high-performance batteries in a range of increasingly challenging applications; for example, in the automotive sector, drivers want to charge their cars quickly, but also have extended driving ranges to overcome range anxiety. So, engineers are looking to design batteries that can store more energy and deliver it quickly.

A battery's power capability is measured by 'C-rate': 1C is the equivalent of charging/discharging a battery to its full capacity over one hour, while a rate of 10C is equivalent to dispatching the same capacity in six minutes. In the EV sector, the ability to charge at high C-rates provides an opportunity to 'refuel' cars in an acceptable time (compared to expectations built by the time it takes to refuel a combustion engine vehicle), and during discharge provides an opportunity to match, or exceed, the performance of conventional vehicles.

The amount of energy stored in a battery is generally determined by how much material is present in the active

MANUFACTURING



European Li-ion gigafactory battery manufacturing capacity to 2020 © The Faraday Institution

As demand for battery manufacture grows, and governments recognise the need for domestic manufacture (in particular to support the automotive sector), the geography of battery manufacture has diversified. While China retains the largest battery manufacturing capability, projected growth of gigafactories in Europe is also increasing significantly, as demonstrated in the figure above. In the UK alone, the potential domestic demand equates to approximately 10 gigafactories by 2040, according to research from the Faraday Institution.

Manufacture of this magnitude is needed to keep prices competitive. However, there are growing imperatives for security of supply and decarbonisation of the battery manufacturing sector. In Europe, this has led to the integration of manufacturing with clean energy supply: recent estimates reveal that in manufacture up to 65 kWh of energy input are required per kWh of battery produced. Ambitious sustainability targets could also lead to improved manufacturing yield and a requirement for improved process monitoring and quality control.

electrodes within a cell (which are those that participate in the chemical reaction). By contrast, the power density is generally determined by the electrical and ionic conductivities of an electrode. This means that, when developing a battery, engineers must carefully address competing requirements for energy and power density so that a cell can be tailored to its use: a high-energy cell requires low porosity electrodes with a high packing density of active materials, while a high-power cell favours thinner electrodes with high porosity and high conductivity.

Engineers must also consider the balance of volumetric and gravimetric energy (and power) density. In consumer electronics and passenger vehicles, batteries that can store the maximum energy per unit volume have been carefully optimised over many years (enhancing volumetric energy density). However, with growing uses in the aviation sector an emerging challenge is to make lightweight batteries (with enhanced gravimetric energy density).

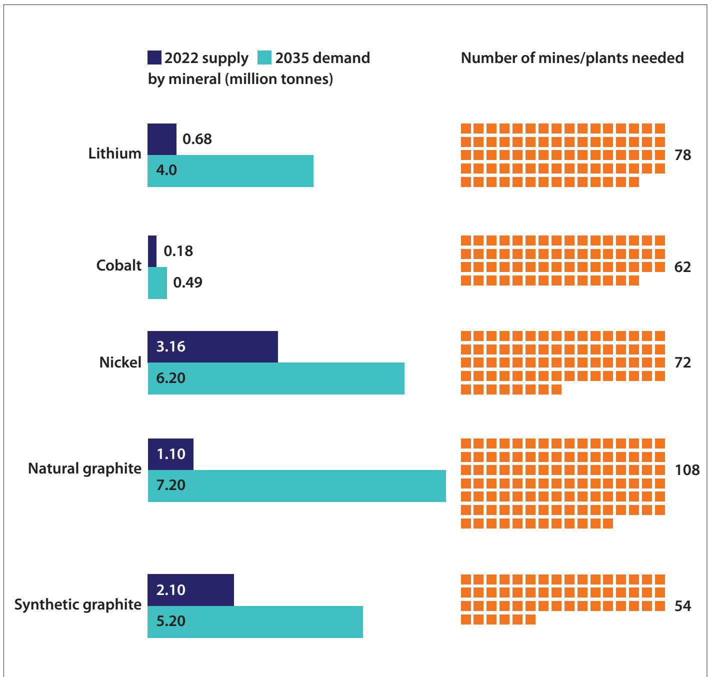
Academic and industrial engineers are also carrying out substantial research into battery degradation. While recent research has promised a 'million-mile battery', current technologies usually do not come close to achieving this. A critical measure of degradation is the capacity fade (capacity loss over time) and in general a battery in an EV is deemed to have reached end of life once this falls to 80% of the original rated capacity. This occurs alongside power fade, which impacts a vehicle's ability to charge/discharge at a high rate and is considered to be of equal (or perhaps greater) importance by the automotive industry. Extending a battery's lifetime before these critical thresholds are crossed is central to minimising a battery's lifetime cost and providing confidence to adequately warranty batteries in service. Many processes impact battery lifetime, including the operational voltage limits, maximum charge and discharge current, and temperature. All of these variables are monitored and controlled by a vehicle's battery management system (BMS), and for lifetime and safety reasons, the BMS often applies a conservative control strategy, which can limit the battery performance.

POST LI-ION TECHNOLOGY

As projected improvements to Li-ion batteries' performance begin to plateau, these remaining challenges have motivated the search for next-generation battery chemistries. Fortunately, there is no shortage of possible contenders, offering batteries with lower cost, improved sustainability and safety, and higher performance. These include:

Solid-state batteries: conventional batteries use liquid electrolytes, and in the case of Li-ion batteries, contain non-aqueous and flammable solvents. The volatility of the electrolyte is one of the main challenges in designing inherently safe batteries. Solid-

SUSTAINABILITY



The critical minerals needed to meet global battery demand by 2035 (redrawn using figures from Benchmark Mineral Intelligence article 'More than 300 new mines required to meet battery demand by 2035', September 2022, and 'Asian battery makers jeopardise raw materials access by delaying deals', ft.com, November 2022)

Across the breadth of battery usage there are complementary challenges in reducing costs and improving the sustainability of materials supply and battery manufacture. Removing components from the battery that are expensive to source, and where supply chains are unethical, unsecure and unsustainable, is critical to contributing towards net zero. The well-documented reliance on cobalt is particularly important, because raw materials supply is largely confined to areas of low geopolitical stability, including the Democratic Republic of Congo. Over the past decade, there has been a reduction in the amount of cobalt used in state-of-the-art batteries and it has been systematically replaced with nickel and manganese. However, cobalt is not the only scarce element found within a battery, and the EU's Critical Materials list documents the pressure on lithium and natural graphite supply chains, as well as a watching brief on nickel. Given the rapid acceleration of the battery manufacturing sector, securing ethical and sustainable supply chains is a growing challenge that will require a significant growth in raw materials extraction. It is also essential to improve battery recycling infrastructure to establish a circular economy for the sector.

state batteries combine a wider class of battery technologies, where the liquid electrolyte is replaced by an ion-conducting solid, generally an oxide or sulphide material. Removing the flammable components has obvious safety benefits, but also provides the framework to re-examine the use of metallic electrodes. Historically the use of lithium metal electrodes has been hampered by the growth of dendritic lithium (microstructures that resemble whiskers). These, on repeated cycling, eventually short circuit the cell. The solid-state electrolyte provides a physical barrier to dendrite growth and was therefore widely expected to avoid this issue. However, it was discovered that above critical current densities, highly mobile lithium could still penetrate the solid electrolyte, leading to short-circuiting. Researchers are currently looking at several strategies to address these issues (for example by applying external pressure). If successful, the solid-state battery promises high energy density and safe energy storage.

Na-ion batteries: as a raw material, sodium (Na) is substantially more abundant than lithium, providing an opportunity to improve the sustainability and security of supply. Na-ion batteries operate via similar principles to Li-ion, wherein sodium ions are transferred between solid electrodes via a liquid electrolyte. While Na-ion batteries have a lower energy density, the cost benefits of the technology make it an attractive alternative for some applications and it can easily 'drop-in' to existing Li-ion battery manufacturing infrastructure.

Li-sulphur batteries: sulphur is an abundant and cheap commodity chemical, often considered a by-product of industrial processes, and the LiS battery offers the possibility for a low-cost and high-energy battery. Unlike Li- and Na-ion batteries, the solid sulphur positive electrode reacts with lithium to form soluble (liquid phase) products. This reaction can occur over a wide temperature range, and is fundamentally different from the solid-state reactions that typically happen in conventional batteries. Understanding this process, and mitigating against the active material loss that can arise from the 'polysulfide shuttle' mechanism is central to further developing LiS batteries. Engineers will also need to overcome other challenges associated with the electrically insulating nature of sulphur, and the comparatively low power density of the LiS system, but there is significant promise to offer a battery optimised for lightweight applications.

SUPPORTING NET ZERO

'Electrify everything' using renewable energy is one of the key strategies to reach net zero. Energy storage, where batteries can play a central role, could meet wide-ranging energy use (across stationary, mobile and transport applications), and compensate for the intermittency of wind and solar generation. Li-ion batteries have already substantially reduced emissions through decarbonised road transport, particularly in passenger vehicles. However, this also highlights the need to integrate decarbonisation across the energy system, including in manufacturing.

As we progress towards 2050, the plateauing performance of Li-ion batteries, alongside increasingly challenging applications, will require the introduction of a portfolio of batteries. This will collectively provide opportunities to improve cost, safety, performance, and sustainability. There are already several substantial, coordinated research programmes targeting these goals, including the UK's Faraday Institution, which brings together research scientists and industry partners to tackle scientific challenges and explore projects with commercial potential. Investing in these next-generation batteries could effectively matchmake the right battery with the right application helping to engineer a net zero world.

SAFETY

While battery failures are rare (estimates suggest one in 40 million batteries might undergo catastrophic failure), understanding and preventing 'thermal runaway' in batteries is of paramount importance. Thermal runaway describes a situation wherein a failure in a battery (for example, a short-circuit or over-voltage) leads to an exothermic chemical reaction that releases heat and increases the battery's temperature, in turn generating further exothermic events. Once the rate of heat generation in the battery exceeds the rate of heat rejection, there is a risk of thermal runaway and catastrophic failure. The cell's increasing pressure and temperature, and the flammability of some of the internal components, can lead to explosive events. For example, in 2016, Samsung hit the headlines when it recalled a large number of mobile phones because of battery failures. Sophisticated safety strategies involving both hardware (pressure relief vents, current interrupt devices and positive temperature co-efficient resistors) and software (temperature and voltage monitoring via the battery management system) help reduce the risk of thermal runaway, and its spread to neighbouring cells in a pack (see 'How does that work? Lithium-ion batteries', *Ingenia* 69). However, further understanding of the science of battery safety is required, alongside novel solutions for intrinsically safe battery systems.

BIOGRAPHY

Professor Paul Shearing co-directs the Electrochemical Innovation Lab at UCL. Launched in 2011, it is now one of Europe's leading centres for technological innovation in electrochemical technologies. He is a co-founder of the Faraday Institution, the UK's independent institute for electrochemical energy storage research, and is a member of its Expert Panel. As a founder of the STFC Batteries Network, he has acted as an ambassador for UK science on an international stage, and frequently advises the UK government on policy matters.

A BMW i4 is subjected to a 32 km/h side pole crash as part of the Euro NCAP test programme © Thatcham Research

ENSURING A SAFE IMPACT

Crash testing is used to ensure safe design standards for modes of transportation including cars, aircraft and wheelchairs. As well as the test itself, the process involves data analysis and carefully monitoring the position and shapes of the dummies used. Dr Anna Ploszajski spoke to Alex Thompson, Principal Engineer for Automotive Safety at Thatcham Research, about the steps involved in vehicle crash testing and how crash test dummies are developing to be more representative of the general population.

Did you know?

- Impact testing is a form of destructive testing used to assess safety of road vehicles
- Crash test dummies didn't exist until the 1970s, before which cadavers, live human volunteers and even animals were used in testing
- Until recently, only three models of dummy were used in testing and these didn't represent the average woman
- In a high severity test, the crash itself takes just 200 milliseconds

Each year, there are around 126,200 road accidents in Great Britain. On average five people a day die on the road, while 84 are seriously injured. Safety of the vehicles we drive and use is critically important. To give consumers transparent information about the cars they are choosing to buy, every new model of car that goes on sale in the UK must undergo impact testing to assess its safety, provide consumers with a guide to that safety and give manufacturers clear safety requirements.

A form of destructive testing, impact testing is often used to assess the safety of road vehicles. It also extends to other modes of transport, such as rail, aircraft and wheelchairs; protective clothing such as hardhats and protective vests; and packaging.

The process typically involves simulating an impact in a controlled facility. This could be, for example, crashing a moving vehicle into a wall and gathering data from high-speed cameras, triaxial accelerometers, and a host of sensors embedded in crash test dummies to measure the potential damage in different impact scenarios. A team of design engineers, materials engineers and computer simulation engineers then use the data to improve safety design of what's being tested, whether a vehicle, item of protective clothing or even packaging.

"…Our aim is to reduce the number of people who are killed or seriously injured on European roads," says Alex Thompson, simply. As well as being Principal Engineer for Automotive Safety at Thatcham Research, Thompson is a lead inspector for Euro NCAP (the European New Car Assessment programme), which tests cars and provides independent safety ratings to consumers.

"At the other end of the scale, we also perform 'low severity' crash tests that represent the type of crashes that occur most frequently – that's those at a much lower speed than the Euro NCAP tests, where occupants are unlikely to sustain any injury but the vehicle can still sustain a significant amount of damage." The results of these tests inform insurance companies of how much damage a car might typically sustain from everyday, low-level impacts. "The aim there is to encourage vehicle manufacturers to design more repairable vehicles with affordable parts, and therefore reduce the cost of a vehicle's insurance premiums and reduce waste," he says.

HOW TO TEST A VEHICLE

Assessing a vehicle for Euro NCAP involves four different 'high severity' crash tests, and other tests and assessments for how vehicles behave in a crash, as well as how good they are at preventing a crash from happening in the first place.

"It's very exciting," says Thompson. "We stand in the crash facility in a viewing area. All the lights go on. We have to have very bright lights for our high-speed cameras, that are running at 1,000 frames per second. We then make sure that everyone knows what's happening and the test engineer knows we're recording data.

"Next, we have a countdown. In our facility, the vehicle starts out of sight. And our winch that tows the vehicle makes quite a bit of noise as it ramps up. There's a build-up of noise as you get towards the point of the impact.

"You get a woosh as the vehicle comes into the facility. In

An engineer inspects the damage and takes post-crash measurements © Thatcham Research

Crash test dummies must be positioned very accurately to ensure that test results are valid
© Thatcham Research

a typical frontal impact test, it's about 40 mph (64 kmph) and most people comment that it looks really fast.

"At this crescendo of noise, the vehicle comes into the facility and then there's this almighty bang. And most people are quite shaken by that. It's very dramatic. The vehicle rebounds, and it's over in the blink of an eye.

"I think people are shocked and a bit stunned at both the noise and then the aftermath of the crash, when all of a sudden the car is wrecked. The airbags have gone off. Then the winch motor dies and everything goes a bit silent."

DATA AND DUMMIES

Once the test has taken place, the team needs to document it by taking photos before and after to show exactly what happened, and data from the dummies and vehicles is downloaded and processed "We look at the high-speed films and, in combination with the data, we look at how the dummies have reacted during the impact, and whether the airbags have deployed correctly," adds Thompson.

After the test, engineers must understand what the results might mean for real-life users of the car in question. Therefore, they need to set up the tests incredibly accurately.

Crash test dummies are highly engineered, fitted with hundreds of sensors and transducers that can tell crash test engineers what the likely effect on a living human occupant might have been in any given crash test. For example, the dummies developed by Humanetics – the largest manufacturer of crash test dummies – are fitted with sensors that indicate whether an occupant would suffer broken bones or damage to soft tissue.

"There are very small tolerances about how you position a dummy," explains Thompson. "For example, we have a reference point on the dummy called the h-point, which is where the standard hip is. We have a tolerance of plus or minus 13 millimetres to position that dummy. So for that vehicle, for every crash test that happens, we should be within that window." This level of accuracy allows the tests to be directly compared across different vehicles; any variation in dummy positioning would introduce too many variables.

However, humans do not sit in the same way as crash dummies. Thompson adds: "So, afterwards, we have to strip the car down and look at what might have happened if the dummy was sitting in a slightly different position. For example, where the knees may have impacted the fascia [part of the dashboard], we need to check if there are any hazards [such as other structural components in the car] around that area so that if a driver was sitting in a slightly different position to the dummy, is there likely to have been a worse performance than we saw in the test? We also have to look carefully at the vehicle structure, to see that if the crash was at a slightly higher speed, different overlap, different impact angle… we would likely have seen a significantly different result."

Importantly, crash tests don't promise to predict what would happen in any given crash scenario in a particular car. Rather, the tests provide a way to compare against other vehicles and provide a general overview of safety performance – what you might expect to happen to occupants, pedestrians, and the vehicle itself in a crash – as well as safety equipment in the vehicle such as airbags and autonomous braking systems. But it doesn't come without its challenges.

FACING THE CHALLENGE

The biggest challenge with impact testing comes from its nature as a destructive test, so it needs to be right first time. "The most expensive I've personally tested has been well over £100,000 as a brand-new car," says Thompson. "So, yeah, we simply don't have a second opportunity."

Part of the difficulty is the degree of accuracy required. "We have tolerances on the speed of impact that we need to achieve," says Thompson. "For example, for a 64 kmph frontal impact test, we start the vehicle 80 metres away, and we have to hit the barrier that we're impacting within a 20 millimetre tolerance. So, we have to be certain when we set everything up that it's going to hit correctly. As well as that, making sure all the data is going to record, cameras are going to work. That's really key."

To mitigate the risk of a wasted test, preparation is everything. The team takes three or four days to prepare for a test and it has lengthy checklists. The crash itself takes just 200 milliseconds, followed by several days of data analysis. "We have to be absolutely spot on with everything that we're doing," adds Thompson. "Double checks, triple checks… and we have to not be afraid to say we're not going to test it if there's anything that flags up as being a concern."

CONTROVERSIES

In 2019, the Center for Applied Biomechanics at the University of Virginia published a study that found that women were 73% more likely to be injured than men in a frontal crash of the same speed and severity. Women are also three times more likely than men to suffer from whiplash injuries in rear impact crashes. These figures suggest that current vehicle design disproportionately benefits drivers who are men.

Today, there are three types of crash test dummies for adults used by EuroNCAP and the American equivalent, the National Highway Traffic Safety Administration (NHTSA). The '95th percentile male' (188 cm tall and 100 kg), the '50th percentile male' (175 cm tall and 77 kg) and the '5th percentile female' (152 cm tall and 50 kg). These standards were developed in the 1970s and have remained the same ever since. (Before the 1970s – and even afterwards – cadavers, live human volunteers and animals such as chimpanzees, bears and pigs were used as crash test dummies.)

On the face of it, this sounds as if crash test dummies would represent most road users. "The 5th percentile female dummy takes into account a shorter driver that is sitting much closer to the steering wheel, and also a shorter rear occupant," says Thompson.

But these 'female' dummies are merely scaled-down versions of the larger ones. Their proportions and body shape are the same as those of the male dummies, and they are roughly the size of a 12-year-old girl, not an average woman. The lack of representation of women road users in crash testing could go some way to explaining the discrepancy of road injuries by gender.

Fortunately, more realistic dummies are out there. In October 2022, a team of Swedish engineers led by Dr Astrid Linder developed the first crash test dummy designed to match the body shape, size and weight of an average woman (162 cm tall and 62 kg). Although these dummies are not yet a legal requirement for user tests such as Euro NCAP, Humanetics has developed dummies that represent road users who are 'elderly', 'large and obese', children of different sizes, and a 5th percentile female dummy with an adult woman's shape. If and when regulations do change to include such diversity of dummies, it will be interesting to see whether vehicle safety design changes in response, and whether the real-world fatality figures improve for women and other vulnerable road users.

It is vital that engineers working in crash testing and vehicle safety policy are representative for the full spectrum of road users, to make everyone as safe as their '50th percentile male' counterparts.

Hybrid-III 50th percentile male and 5th percentile female frontal impact crash dummies © Thatcham Research

SAVING RACING DRIVERS

Impact testing has also revolutionised the world of motorsport. Engineers developed the Halo driver crash protection system using impact testing. The first tests using the technology started in 2016, and since 2018, the Fédération Internationale de l'Automobile (FIA), motorsport's governing body, has made it mandatory on all vehicles raced in Formulas 1, 2, 3, 4, Regional, and E.

The Halo is a structural feature on cars driven in these categories of race. It is made of titanium, surrounds the driver's head and is connected to the vehicle frame in three places.

Using data from 40 real incidents, the FIA performed crash test simulations of vehicles with and without the Halo structure, in different scenarios: collision between two vehicles; contact between the vehicle and the environment, such as course barriers; and collisions between the vehicle and debris. They found that the Halo theoretically increased the survival rate of the driver by 17%.

The safety system attracted some criticism early on, with opponents complaining of its ugly aesthetics. However, several serious crashes following its adoption demonstrated its life-saving capability. Halos have been landed on or struck by other cars, crashed into barriers, and even taken the entire car's

The Halo – the black T-shaped curved structure – is used on vehicles in motorsport racing to protect the driver's head in crashes and from debris © Shutterstock

weight when they've been flipped upside down; in all cases, the drivers attributed their survival to the Halo.

THE FUTURE OF IMPACT TESTING

Impact testing must keep pace with the constantly changing landscape of vehicles on today's roads. Consumer vehicles are changing rapidly, with additional safety technologies such as autonomous emergency braking becoming standard.

For example, the Global Vehicle Target was first introduced by Euro NCAP in 2014 to test autonomous emergency braking systems. These systems use sensors, such as cameras, radars and lidars, to detect potential hazards in front of the vehicle, and automatically apply the brakes to avoid a collision or mitigate its severity. For these tests, the impacts on real vehicles are tested on a remotely controlled 'soft car' that travels at speeds of up to 144 kmph and is recognised as any ordinary car would be by sensors on autonomous cars. Although it might disintegrate on impact, it can be reassembled in a matter of minutes, making it a lot cheaper than totalling a real car.

There are also assessments for systems designed to avoid collision with pedestrians and cyclists. As the vehicle systems change, the assessments must constantly evolve too, and EuroNCAP has added different scenarios to its tests since their first introduction, such as braking when a car turns across the path of an approaching vehicle.

"Over the next 50 years, we're still going to see cars crashing," says Thompson, "but we're going to see cars crashing in different configurations as these systems potentially intervene and mitigate collisions."

For example, if a car has already autonomously started to brake before a collision occurs, it is possible that the occupants might be in a slightly different position than they were before the brakes were applied. And, as vehicles become even more automated, we might see occupants reclining to take a nap or turning their seats round to chat or play games with the other occupants in the car. So, crash testing will need to adapt to these different scenarios.

"As these new technologies change the way that people use their vehicles and change the way that vehicles interact with each other, it'll be vitally important that, if you do have a crash in that situation, you'll be protected as you would be now."

CAREERS IN IMPACT TESTING

It was an undergraduate degree in mechanical engineering and answering a job advert for crash test engineers that led Thompson down his career path. Other routes into working with crash testing include apprenticeships to become a crash test vehicle technician. But for Thompson, the choice was also a personal one.

"My grandfather was involved in a very serious accident when I was a kid," Thompson says. "Without endorsing any particular brand, he was driving a Volvo, which was designed with a crumple zone. He went head-on into an HGV, and this was pre-airbags. But he survived, in a type of crash which, in those days, you potentially wouldn't have done. So, I was very passionate about furthering vehicle safety.

"In terms of a career within engineering, it's a very rewarding one. Having been in it for 22 years, you can see the change in vehicle design as vehicles have gotten safer and more safety equipment has been fitted. It really gives you a sense of pride in the work that we've done as crash test facilities and safety organisations in helping reduce the number of people who are killed and seriously injured on the roads."

BIOGRAPHY

Alex Thompson is Principal Engineer for Automotive Safety at Thatcham Research. He started his career in crash testing in 2001, and has lost count of the number of cars that he has destroyed in the name of improving vehicle safety, both through consumer testing and research programmes. He is a Chartered Engineer, a Euro NCAP Lead Inspector and Thatcham's subject matter expert for vehicle safety.

MX3D's 3D-printed bridge being opened by Queen Máxima of the Netherlands in Amsterdam in July 2021 © Adriaan de Groot

3D PRINTING A BRIDGE WITH A TWIN

Did you know?

- Sensors are being embedded into structures new and old, from tunnels to bridges, so that engineers can monitor whether repairs are needed using so-called 'digital twins'
- Data from these sensors could help engineers design smarter structures, for example with less material to save CO_2 emissions
- A canal bridge in Amsterdam – the first ever 3D-printed steel bridge – has had a digital twin created, so engineers can demonstrate what they are capable of

The world's first 3D-printed steel bridge showcases technology that could reduce the amount of material used in structures. It has a network of sensors that continuously feed data into a 'digital twin' that will monitor how the bridge behaves over time and help refine the design of similar structures in future. Hugh Ferguson reports and looks at how a similar approach to monitoring is being adopted across civil engineering projects.

In Amsterdam's red light district, a bridge unlike any other stretches across the Oudezijds Achterburgwal canal. It's strikingly different from the brick arches elsewhere in the city, with bicycles locked to metal balustrades. But it's not just its appearance that's different.

This is the world's first 3D-printed steel bridge, and it is outfitted with over 100 sensors that measure loads applied to the bridge, wind, air quality, and much more. This makes it more than a footbridge, and more than a design object. It is a living laboratory, a testbed for digital twins (see 'Creating a virtual replica', *Ingenia* 87) of public infrastructure.

The data collected from its sensors are sent to the Alan Turing Institute in London, where it will feed into a continuously updated digital model, or 'digital twin', of the bridge. Engineers will use this to monitor it in real time, while the City of Amsterdam will use it to analyse pedestrian behaviour. But importantly, it will also fuel research into digital twins of structures that will help optimise future designs, enabling engineers to reduce material use and, as a result, carbon emissions.

AN ELABORATE PUBLICITY STUNT

The origins of this bridge lie within a small creative design studio in Amsterdam, Joris Laarman Lab, headed by designer and artist Joris Laarman. In about 2014, excited by opportunities presented by emerging technologies, the team decided to develop designs in 3D-printed stainless steel. This presented an immediate challenge: no-one had before produced large steel objects using 3D printing or additive manufacturing.

The process requires molten metal to be deposited in multiple layers. At the time, there were already tools for metal inert gas (MIG) welding. In this arc welding process, a continuous solid wire – usually 1.2 millimetre in diameter – is electrically heated and fed from a welding gun. There were also robots on which the tools could be mounted. However, no-one had used robots with MIG welding. Robots were generally used for repetitive 'pick and place' tasks, rather than complex welding control.

The main challenge was to create software to control such uniquely programmed toolpaths. So, the team formed a startup, MX3D, invested in equipment and started to experiment.

MX3D recognised that it needed publicity to get further support. So, the team started producing eye-catching objects, including chairs and bicycles. But from the start, they realised that a steel bridge would put them on the map. And where better to get noticed than across the Oudezijds Achterburgwal, one of Amsterdam's oldest canals, where millions would see it?

Even before a design was firmed up, MX3D's efforts at publicity proved extraordinarily successful. A number of international bodies came to join the project as partners, including software company Autodesk and steel manufacturer ArcelorMittal. The structural engineers at Arup helped to create a new design. Universities also became involved, including Imperial College London for testing, and the Alan Turing Institute for creating a digital twin.

PRINTED BY ROBOTS

The team worked with Arup to create a new design, starting with a simple U-beam section to span the 8.5-metre-wide canal, on Arup's advice. Arup added design loads to a finite-element model of the bridge and presented pictures of the stress patterns. These inspired Laarman to adjust the design.

Printing of the bridge underway at MX3D's workshop in Amsterdam © Olivier de Gruijter

He used them to guide the structural appearance – to add extra material thickness where more strength was needed or subtract material in places with lower stress.

The materials and design fell outside the normal design codes that govern bridge structures, so universities including Imperial College London undertook a major programme of testing, starting with small samples and concluding with a full-scale load test of the completed bridge. These confirmed that the material's characteristics were similar to conventional stainless steel.

Four robots, each with six-axis arms, then printed the full 6,000-kilogram bridge in six months in MX3D's workshop. A full-scale load test, with the maximum design load of 20 tonnes, then confirmed the bridge's overall strength.

To simplify construction, the team printed the bridge in several parts and transported it by road and boat from MX3D's workshop. The central structural section spans the canal, with paving added later, while the ornate flourishes at either end were manufactured separately and welded on.

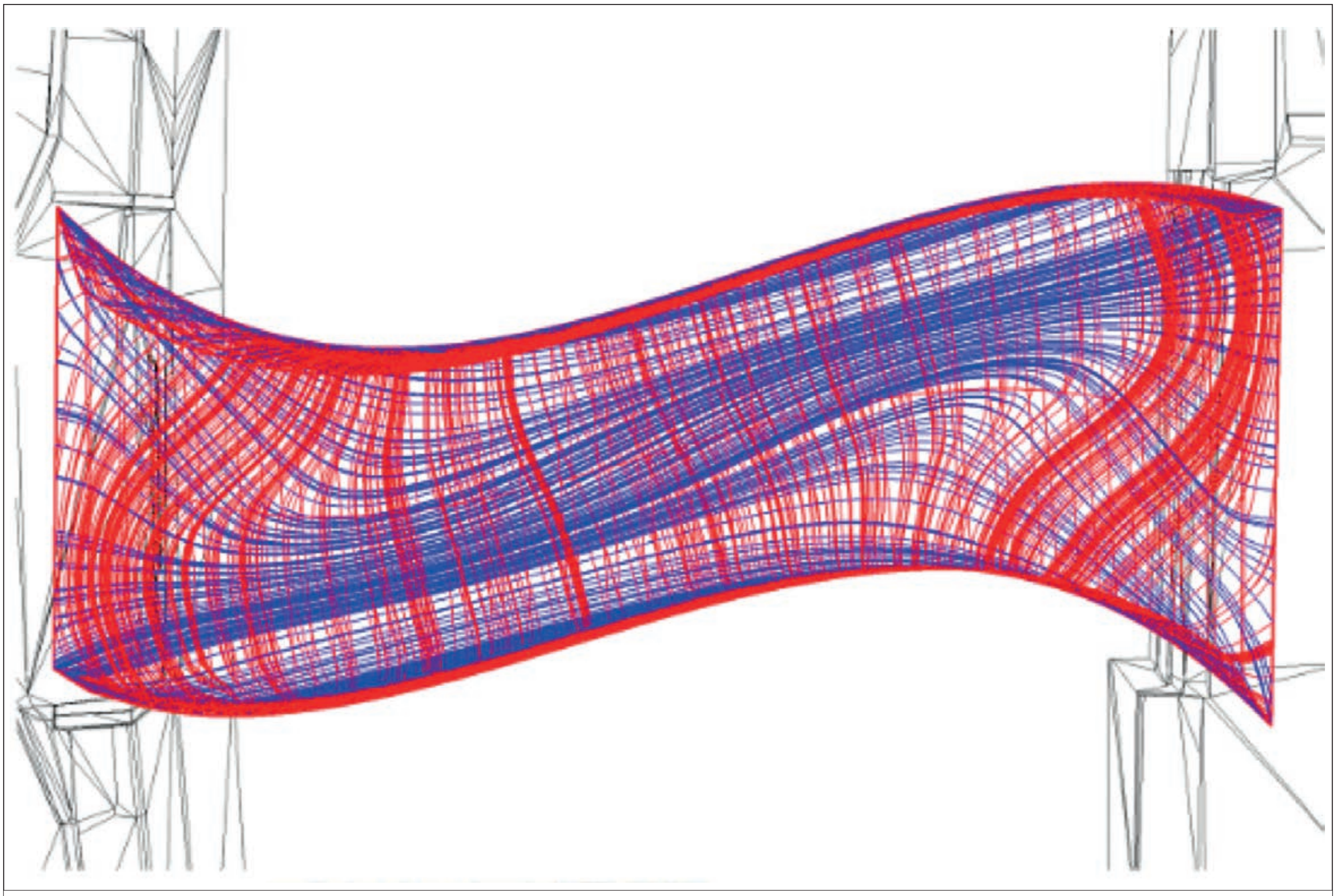
DIGITAL TWINNING

Meanwhile, the Alan Turing Institute in London, the UK's national institute for data science and artificial intelligence, and Professor Mark Girolami FREng, its Chief Scientist, became interested. It adopted the bridge as a testbed and demonstrator for digital twins in construction as part of its datacentric engineering programme.

The bridge has been fitted with more than 100 sensors that measure strain, displacement and vibration, people-flow and the loads they apply on the bridge. The sensors also measure environmental conditions, including issues relating to natural corrosion, wind, thermal, light, and air quality.

As an example, measuring 'natural corrosion' means that if in several years' time the strength of this new material started to deteriorate, the digital twin would spot this long before there were any visible indicators. Some others (such as wind) are less relevant to this bridge, but could be very important on a suspension bridge, so are more significant for this bridge as a demonstrator for digital twinning on structures in general.

The data from these sensors is sent to servers in a basement room adjacent to the bridge, before being transmitted directly to a control centre at the Turing Institute. It will not only help engineers to monitor and maintain the bridge over time, but will also fuel more research into machine learning, data analytics and management, and



The stress analysis performed by Arup © Joris Laarman Lab

optimised design. This will help show what can be achieved with digital twins.

BRINGING DATA TO THE FOREFRONT

The work of the Turing Institute in creating a digital twin for the Amsterdam bridge is an important steppingstone in a career-long campaign by Lord Robert Mair CBE FREng FRS, Emeritus Professor of Civil Engineering at the University of Cambridge, to persuade members of his profession to measure the performance of what they create. His work is being continued by Professor Girolami, who is successor to his chair at Cambridge.

Lord Mair believes that civil engineering is a conservative profession, and that other sectors – notably aeronautics, automotive engineering and electronics – are upgrading and improving, with leaner and smarter design, because they measure what they do. Design, he believes, should be performance-based: measure what you build, and use the data to maintain existing structures and improve the design of new ones.

"I'm a huge fan of civil engineering," he says "but we are ... doing the same old designs, same old codes of practice, same old methods, which were all founded around uncertainty – because we don't know how something actually works."

Decades ago, he was consulted about London's Tube tunnels. He was asked about the life expectancy of the 100-year-old Northern Line, and concern about movement of the 1970s flexible tunnel linings at Bond Street. In both cases, his advice was to insert strain gauges to measure movement over time. If there was no movement, then 'if it ain't broke don't fix it', but keep monitoring. If movement was detected, then the scale and speed of the movement would indicate what needed to be done.

Later, on his advice, strain gauges were cast into the concrete tunnel segments of London's new power tunnels before construction. This meant that performance of the tunnels could be measured over decades to come – a world first.

He also established the Cambridge Centre for Smart Infrastructure and Construction (CSIC), largely to persuade the industry to adopt such measurement and monitoring as a norm. At the same time, there were major developments in data, wireless technology and fibre optics, all of which helped with improving measurement.

The adoption of modular construction has also furthered the cause. Since key elements are fabricated in a factory rather than on site, sensors can easily be embedded in the structure

The central structural section of the bridge being transported to its final location © Merlin Moritz

(as with the Thames Power Tunnels). This is more reliable than adding them on later.

STRATEGIC MAINTENANCE, FUTURE DESIGN

A major advantage of closely measuring structural performance is that it enables more strategic maintenance. Network Rail has a major continuous programme of visual inspection and maintenance of its vast infrastructure. It asked CSIC engineers to install 200 fibre-optic strain gauges into two new bridges in Staffordshire to detect the real stresses as trains pass over, as opposed to those assumed by the designers (*Ingenia* 87).

The first result was to reveal that the bridges are much stronger than needed to carry the loads required. As a result, future bridges could be designed and built with less material – at a lower environmental and economic cost. Longer term, the sensors will continuously feed back data on the bridges' performance, revealing the need for repairs.

CSIC was also asked to look at a large Victorian railway viaduct through Leeds, which Network Rail was planning to demolish and replace. Installing strain gauges revealed that the bridge was actually performing remarkably well under the loading from high-speed trains, despite alarming cracks in the masonry. This £30,000 investment saved tens of millions of pounds for replacement, and the sensors remain to detect any future deterioration. Repeated over Network Rail's whole network of structures, this approach could greatly reduce the amount of visual inspection needed and help to prioritise where maintenance is most needed.

The approach can also inform future design, so that engineers can reduce CO_2 emissions

Monitoring Crossrail tunnels at Liverpool Street station showed that far more reinforcement than necessary was used to strengthen tunnel linings at junctions with crossover passages – with a potential saving of £1 million per station

associated with construction projects, along with overall costs. In one example that hinted at what was to come, CSIC engineers inserted fibre-optic strain gauges into the huge circular concrete shafts for both Crossrail and Thames Tideway in London during construction. The shafts were designed as a series of large retaining walls, crammed full of steel reinforcement to resist bending from the pressure of the surrounding earth.

The sensors revealed that the bending was actually minimal, meaning future such shafts can be designed with far less reinforcement, and substantial cost (and CO_2) savings. Similarly, monitoring Crossrail tunnels at Liverpool Street station showed that far more reinforcement than necessary was used to strengthen tunnel linings at junctions with crossover passages – with a potential saving of £1 million per station.

Lack of knowledge about how structures actually behave has meant that current standards and Codes of Practice embody large factors of safety to cover uncertainty. As the availability of data improves our understanding of real structural behaviour, some of these standards could potentially be relaxed. Of course, for very good reasons, changing Codes of Practice takes time and should be proceeded with cautiously. Lord Mair can see, for example, piles being 10% less thick and retaining walls up to 20% less thick, with huge savings. The data will also assist the creation of codes and standards for new materials, such as 3D-printed steel.

Digital twins are an extension of this philosophy, now made possible by technological developments such as the ability to store and analyse vast amounts of data. For every future infrastructure project, Lord Mair and Professor Girolami would like to see a digital twin created in parallel with the design – and not a spade put in the ground until the digital twin is complete. Then, data from the digital twin could inform the construction process, while data fed back from sensors during construction could help refine the digital twin.

Currently, a typical project may be designed and supervised by a consulting engineer and handed over to the client on completion, together with a 'good luck' message. Mair would like to see the digital twin handed over as well, continuously monitoring the structure in use and providing 'red light' warnings if anything should go awry. The Amsterdam 3D-printed bridge is perhaps the most highly developed example so far. Then, the use of the digital twin could go further. Professor Girolami likes to quote the English statistician George Box who said, 'all models are wrong'. This is because of the inexact assumptions within them, and applies even to sophisticated finite-element models (FEMs) used to design the most complex structures.

If real-time data from the bridge was fed into the FEM used for design, the fidelity of the model could be improved. It would not be as 'wrong' as it was at the start, and it could be trusted more. For example, it could be used to predict how a railway bridge would perform if an overweight train passed over it. And by extension, the FEMs for designing future structures could then be tuned to make them more accurate predictors.

This in turn enables what is called generative design. By establishing a set of criteria and design constraints and feeding in the data given out by the digital twin, engineers can then *generate* many designs that meet these constraints and criteria. This would be a major step forward for structural engineering.

Professor Girolami believes this datacentric multidisciplinary approach to capturing the bridge's data marks a step-change in the way bridges are designed, constructed and managed.

Hugh Ferguson thanks Gijs van der Velden, CEO of MX3D; Professor Mark Girolami FREng, Professor of Civil Engineering at the University of Cambridge and Chief Scientist at the Alan Turing Institute (and formerly Professor of Statistics in the mathematics department at Imperial College London); Professor Lord Robert Mair CBE FREng FRS, Emeritus Professor of Civil Engineering at the University of Cambridge and founder of the Cambridge Centre for Smart Infrastructure and Construction; and Mathew Vola, Project Director in Arup's Amsterdam office, for their help in preparing this article.

DATA-DRIVEN ENTREPRENEUR

Elspeth Finch MBE FREng's career journey spans government policy and transport engineering to software product design. Science writer Michael Kenward OBE talks to her about innovation and how data can change how we manage major engineering programmes.

A common view of engineers is that they build things. Elspeth Finch MBE FREng likes to say instead that her engineering career is about removing friction. Her targets could be the barriers that hindered pedestrians in London's busiest traffic junctions, but more recently she's had barriers to scaling innovation in her sights.

In her career, Finch's focus on user experience (UX) and driving impact has moved from devising ways to create better transport systems towards developing tools and techniques that take a data-driven approach to build enterprise software for engineering companies.

When she was younger and picking career options, science was an obvious candidate: her mother was a medical physicist and her father was a physics professor. There was even an engineer in the family: her grandfather had started out as an apprentice and became a railways engineer. While she originally planned a career in chemistry, Finch soon moved to the applied side of science that had always appealed to her.

Before heading to university, college students in Scotland study more subjects for their 'Highers' than their counterparts in England. Finch took advantage of this to broaden her education studying music and art alongside sciences, an interest that continues in her love of art and design to this day. "Part of the engineering that I do is trying to understand the interplay between design and users."

She also took her first steps along the entrepreneurial road. On discovering that her school planned to produce its first yearbook for graduating students, Finch put herself forward to be editor. "It was a good opportunity, at the age of 16/17, to work out how to build a team, how to go out and get advertising. It was a really safe way to do entrepreneurship in a mini space. I realised that I was quite good at being able to pull a team together. And I really enjoyed it."

CHANGING LANES FROM SCIENCE TO ENGINEERING

With Highers done and dusted, at just 17, Finch went to the University of York to study chemistry. She soon realised that she was more interested in the applied side of science. "I discovered that what I really liked was understanding how to solve problems that affected people directly."

In 1996, a summer internship after she finished her degree gave her a further nudge. Finch worked as a research chemist for a small startup in London and Cambridge that was developing technology to monitor the heart's flow rate. "I wasn't a great research chemist," she admits, but she was exposed to the inner workings of a startup. "The chief exec was really kind and took me under his wing. He gave me opportunities to look at business processes. He let me tag along to meetings with investors." This furthered her appetite for entrepreneurship and secured Finch her first mentor.

Finch followed this summer job with a master's degree in the engineering department at Newcastle University. Keen to study the impact of air pollution on health, she investigated the potential economic and health impacts of fuel cells and electric vehicles on cities. "That's really how I ended up in engineering." The next natural step was to take the master's further, so she moved to The Bartlett Faculty of the Built Environment at UCL and started a PhD on the impact of pollution on people in cities.

At UCL Finch moved into data engineering when she realised that computer models created to support the design of new developments could be valuable for other purposes. The models could benefit not just architects working on buildings but also transport planners and developers. This realisation brought about the hard decision to start a company rather than finish her PhD.

In 2000, still just 24, Finch set up Intelligent Space Partnership, a consulting business that developed software for commercial use as a planning tool, bringing an evidence-based approach to modelling pedestrians in the built environment. She could see a market opportunity in using data to manage things that had previously been hard to pin down. "We built software and developed methodologies around how to better understand things like footfall on streets." This meant putting pedestrians and cyclists into the heart of traffic planning.

Intelligent Space Partnership developed a growing reputation, working on projects in the US, Australia and Germany, leading to its acquisition by Atkins.

INNOVATION FOCUS

Atkins, one of the UK's largest engineering businesses, bought the company in 2007 and recruited Finch as a director. This gave her the opportunity to continue her focus on innovation, moving from entrepreneurship to intrapreneurship.

As Innovation Director for the European region, she could consider innovation on a bigger scale. "I could look at how we could build new businesses within Atkins. We created a network for innovators across the business." The work moved on from bringing together 10,000 people in different parts of Atkins to enabling collaboration with other companies.

Finch is careful in her use of the 'innovation' word. It is the impact that matters, she insists. "Ideas are great, but that's not innovation. For me, innovation is when you deliver impact. That might be the growth of a company, it might be

FOLLOW THE DATA

Intelligent Space Partnership was part of the team that addressed the intersection between Oxford Street and Regent Street in London's Oxford Circus area, one of the country's busiest stretches of pavement © Shutterstock

Finch realised the value and importance of data when she moved to the engineering department at Newcastle University for her master's in transport policy with her thesis on the impacts of electric vehicles on cities. She sees data and how to use it as being a big part of her career. "I think data is really interesting, but the hardest thing with data is knowing what questions to ask of it." We're hugely data rich, she adds. Then there are the unknowns. "What's really interesting is not only what data exists, but what are the gaps?"

This goes back to Finch's early work on cities. When she was a part of the team that set out to change Oxford Circus, there was a large data gap. "There was great data on vehicles, but very, very weak data on pedestrians." It's hard to predict what pedestrians will do.

Previously, planning for Oxford Street had revolved around saving time for vehicles. But, as Finch points out, with as many as 40,000 people walking through the area every hour "that's not where the money is". At the time, shopping in London's West End accounted for sales of £9 billion each year. But with no data on the value of pedestrians' time, it was hard to make a business case for development plans.

First, the team gathered data on how people behaved. Camera footage of the area provided the basis for a model that could pinpoint bottlenecks. The architects and engineers used this to redesign the intersection, adding a diagonal crossing to smooth the flow of traffic and pedestrians.

Finch sees a common thread in her career as being the ability to take what people may see as soft measures, such as the number of pedestrians crossing the road, and to turn them into hard metrics, to provide something that can be used as the basis for good decisions. "When we looked at Oxford Circus, the entire business case was based on the time savings for pedestrians."

At IAND – her new company – data mining is very different.

As well as making money, a modern business must meet a raft of non-financial targets, on climate performance and workforce diversity, for example. There are also policies designed to improve innovation and productivity through such measures as the promotion of net zero in the workplace. Therefore companies have board-level committees that handle governance issues such as safety, ethics and sustainability.

IAND's cloud-based platform captures public and confidential data on these and other characteristics. On top of financial reports larger companies must file information on employment practices, including Gender Pay Gap data. The platform uses this data along with, for example, location details of the SMEs that can be part of the wider supply chain. This also sits alongside data on government-funded R&D programmes in businesses of all sizes. Innovate UK, for example, distributes R&D grants to businesses throughout the country. IAND's software can turn these official spreadsheets, with some 40,000 lines of data, into useful information. "We automatically pull in the funding that people have had from Innovate UK," Finch explains. If you can see where the R&D happens, you see where you can work with suppliers to scale up innovation.

Data offers businesses ways to study their performance but trying to wade through everything manually would deter anyone. Finch feels that another thread that pervades her career is the ability to combine a passion for data with understanding the user experience and what people want to do. The company's software engineers have built a data platform that draws on experience from retail e-commerce operations and designed its own interface. "If you want a platform that will save people time, you want it to be intuitive and easy to use."


Finch (far left) joins a panel at an Innovators' Network – the group that she set up to support Enterprise Hub members – diversity and inclusion event in 2017, alongside Academy CEO Dr Hayaatun Sillem CBE (second from right)

QUICK Q&A

What are you most proud of?
Negotiating 50:50 ownership in my first startup when I was 24 as it transformed my career.

Who influenced your engineering career?
Keith Clarke – when CEO of Atkins he not only bought my first company, but has shown belief in me ever since.

What's your advice to budding engineers?
Communication is your superpower – learn how to present, to pitch, to write, to negotiate, to inspire.

Best part of the job now?
My team, my board, my clients. They are brilliant, supportive and I learn from them each day.

Which record/book would you take to a desert island?
Sketchbook (and pen please!).

Your most admired historical example of engineering?
The dome of the Pantheon in Rome – beautiful, ingenious and resilient. And despite being nearly 2,000 years old, remains the world's largest unreinforced concrete dome.

Do you have a favourite gadget?
Apple Pencil: makes it fast to capture and share ideas.

Which engineering achievement couldn't you do without?
The internet, as IAND is on the cloud!

transforming carbon reduction, it can be transforming social value, improving diversity in engineering." Impact can also come from multiple sectors, she adds. "It doesn't have to be financial, but you have to have measurable value."

At Atkins, Finch started to become involved in the Royal Academy of Engineering and its work on innovation. In 2013 she received the Academy's then Silver Medal, awarded for an outstanding personal contribution to UK engineering by an early- to mid-career engineer. The prize coincided with the Academy's launch of the Enterprise Hub, which supports engineering entrepreneurs and SMEs to scale up and exploit their technologies. "It was serendipity," she says. "I managed to get in almost at the ground floor. I've been with them on that journey." The Hub was a natural blend of her own experience, first as the entrepreneurial brains behind a new and successful business and then as Atkins's own promoter and enabler of internal entrepreneurship.

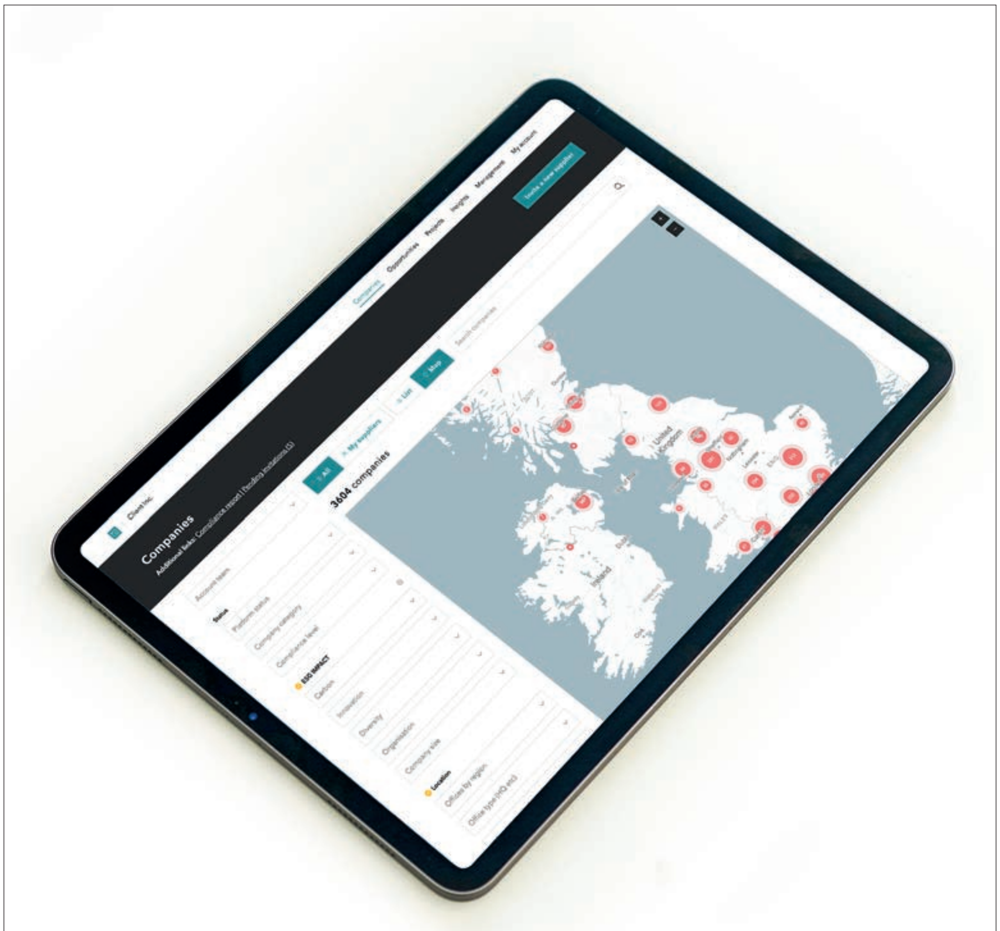
Invited to speak at Hub events and then to participate in various sub-committees, Finch came up with the idea of the Innovators' Network to support the businesses backed by the Hub. "I could see that there was a bit of a gap. How do you bring together the people like me who were driving innovation in big business, and the entrepreneurs behind innovation in small businesses. The Innovators' Network looked beyond the engineering community, enlisting people from the worlds of marketing and finance, for example."

Finch was elected as an Academy Fellow in 2021 and joined the Academy's Enterprise Committee, helping to guide the work of the Hub and the Academy's enterprise activities. "I'm leading the work around creating a toolkit for startups and how they can be diverse and inclusive from start of a business." With diversity high on the corporate agenda these days, and a topic that is important to Finch, businesses of all sizes need to pay attention to the issue, including startups. "It's so much easier to be a diverse business if you start diverse. You can scale up, but it's really hard to retrofit if you're a big company."

SCALING UP INNOVATION

Going back to her entrepreneurship roots, Finch has launched another new startup, IAND. She loved her eight years at Atkins, but as she says, "I knew that I had another company in me." This time she has drawn on her time dealing with suppliers and customers at Atkins.

As she did with Intelligent Space Partnership, which leveraged data to ensure cities worked for everyone not just cars, in 2016 she set up IAND to tackle another hidden problem, the cost and friction of managing relationships with suppliers,



IAND's cloud supplier relationship management (SRM) software is supporting major engineering programmes, such as Anglian Water's Strategic Pipeline Alliance, to gain rapid visibility on where suppliers are located and their spend on local SMEs © IAND 2023 | Example location map

and the data challenge of delivering on increasing environmental, social and corporate governance (ESG) goals.

Her personal experience taught Finch about managing supply chain relationships and also the need for software that supports collaboration and removes the admin burden from engineers and project teams. "I could see the problem from a range of different dimensions," she explains. "I'd had the experience of being a supplier to a big company, working for clients and understanding the governance around how a big company works."

Starting with a blank sheet of paper, Finch was able to rethink how enterprise software could work, creating a diverse team focused on building a great user experience not only for clients managing suppliers, but the suppliers too. The team has been recognised as industry leaders by CIPS (the Chartered Institute of Procurement and Supply Chain) through a recent award. The IAND software is also now used by organisations including Network Rail, Atkins and Mott MacDonald to manage their supplier relationships.

Not long ago that label of supplier relationship management would have meant little outside of practitioners. "It's been a problem that's been a bit hidden from view," she explains. COVID-19 brought wider awareness, especially the scramble for personal protective equipment (PPE), which brought home how supply chains can be vulnerable.

With a focus on simplification, IAND tackled the data challenge of connecting the wealth of data that organisations amass in their own operations, along with public data available on suppliers, to give a full picture of suppliers in one place. The idea grew out of the realisation that today's supply chains are evolving, and the need to have better visibility on suppliers, especially given the need to work with increasing numbers of SMEs.

While companies live and die on the health of their supply chains, government policy is also crucial, especially when it comes to procurement. The government spends about £300 billion a year on products and services, about a third of all public spending. Government procurement can play a key role in encouraging innovation and the growth of SMEs. So, this is another natural target for IAND. Finch brings to this her insights from her work as a member of the government's Innovation Expert Group (IEG), in which she led a subgroup on procurement. "We were looking at how you can use procurement as a lever for innovation," says Finch.

Procurement also comes into the picture when businesses want to bid for government work. They must operate according to a series of regulations covering net zero and social value. These take in measures such as 'prompt payment' to their own suppliers along with net zero regulations that require suppliers to have a carbon reduction plan. Companies don't just have to adopt the regulations, they have to monitor their work and provide evidence that they are following the rules. This is where IAND can play a part.

Companies aren't alone in the need to monitor their activities. Governments also want to check the outcomes from their own actions. As Finch sees it, there is room for improvement in analysing policy implementation. "For me, understanding why some good policies are not delivering the value that they could deliver is an area where there's huge opportunity for change. If I think about the things which really deliver value in scaling up innovation, it's often things that are hugely unsexy. It's procurement, it's contracts. It's understanding how you manage risk."

It is a universal issue that faces any organisation. "How do we make sure that we really understand what the real blockers are for scaling up innovation within organisations? It is about really aligning goals. I think technology can play a huge part in this in terms of really understanding the root cause."

So, what's next? The focus for Finch now is all on scaling innovation. She is supporting the Scottish government in scaling up innovation in Scotland as a member of the Innovation Strategy Steering Group. At the Academy she is supporting other founders in scaling their businesses as a mentor in the Enterprise Hub and as part of the Enterprise Committee. Most importantly, Finch will be leading IAND on its own scale-up journey as it enters new markets, working with new customers to take IAND on the exciting next stage of its growth.

Finch speaks at the Academy's New Fellows briefing in 2021

CAREER TIMELINE AND DISTINCTIONS

Studied chemistry at the University of York, **1993–1996**. Master's in transport planning and policy, Newcastle University, **1996–1997**. Founding partner, Intelligent Space Partnership, **2000–2007**. Operations director, Atkins, **2007–2010**. Futures Director, Water and Environment, Atkins, **2010–2014**. Awarded RAEng Silver Medal, **2013**. Innovation Director, UK and Europe, Atkins, **2014–2015**. Appointed a Member of the Order of the British Empire, **2018**. CEO, IAND, **2016 to present**. Fellow, Royal Academy of Engineering, **2021**.

PERFECTING PAIN-FREE COLONOSCOPIES

Several attempts have been made to create a robotic instrument to carry out visual inspections of the large bowel's interior, making colonoscopies more intuitive and easier to guide. Researchers at the University of Leeds have come up with an instrument that uses what they describe as "intelligent and autonomous magnetic manipulation".

A robotic arm manoeuvres the magnet into place, allowing it to guide the colonoscope through the colon © Mark Webster Photography/University of Leeds

Every year, a million people in the UK undergo a colonoscopy. The procedure involves doctors using a flexible viewing tube, inserted through the patient's anus, to examine the lining of the large bowel and carry out surgical interventions as necessary. Although simple in principle, colonoscopy is a skilled procedure that requires much training and practice to perform well and safely.

A research team in the STORM (Science and Technology Of Robotics in Medicine) Laboratory at the University of Leeds is perfecting an alternative to the conventional system. It uses a magnetically guided instrument controlled by a joystick. The tubes of conventional colonoscopes incorporate a camera, a light source, an irrigation system, and a means of sampling or removing tissue of concern. Using a tube of roughly the same diameter, the new and more flexible instrument has all these facilities. The key difference lies in its tip, which houses a small magnet. Moreover, with the help of artificial intelligence (AI), a robot can conduct the investigations.

Leading the STORM team is Professor Pietro Valdastri, Chair in Robotics and Autonomous Systems. He began working on magnetically guided colonoscopy in 2008, developing it first in Italy, then in the US and, since 2016, in Leeds. "At Scuola Superiore Sant'Anna, we had the idea of using magnetic control to eliminate tissue stretching and pain," he explains. "However, we did not realise how difficult it was to control a magnet inside the human body without knowing its position and orientation."

MAGNETIC GUIDANCE

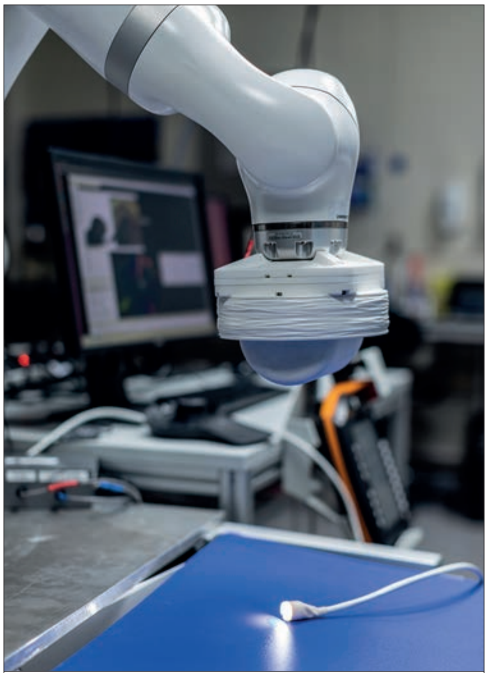
To move and guide the new colonoscope the operator uses another more powerful external magnet mounted on a robotic arm that can move across and around the patient's

EYES ON THE INNOVATORS

***Ingenia* is keeping a close eye on the startups using their engineering know-how to disrupt the status quo.**

Quantum computing startup **Oxford Ionics** has raised an astonishing £30 million in Series A fundraising

Congratulations to **LabCycle**'s Minal Patel – which aims to stop single-use lab plastics going to landfill – as she's named one of 15 southeast entrepreneurs to watch



The magnetic arm and colonoscope © Mark Webster Photography/University of Leeds

abdomen. Steering the tube is impossible without knowing the exact whereabouts of the two magnets. "The key to success," Professor Valdastri says, "was to develop a localisation technique that works in real time so we know the relative positions of the external magnet and the magnetic tip of the instrument inside the body."

With the patient lying on the operating table, the doctor inserts the tip of the colonoscope into the anus. The instrument is steered by a simple joystick and a computer translates its movements to change the position and motion of the external magnet, so varying the direction of the magnetic field that pulls the instrument through the colon. A magnetically guided colonoscope can reach its desired destination at the upper end of the bowel in less time than a conventional one.

This "front wheel drive", as Professor Valdastri describes it, has its advantages. If the colon were a straight tube, simply pushing the instrument to advance it would be fine. In fact, the colon curls round on itself, and while the tip of a conventional colonoscope can be steered, the rest of its length relies on the gut wall to bend it appropriately. The inevitable pressure on the sides of the colon, and its consequent stretching, may cause discomfort for the patient. Guiding the endoscope via magnetism allows the operator to apply force at its tip, pulling rather than pushing the instrument and lessening the pain.

Incorporating AI into the instrument's controls gives the robot partial autonomy. Turning the instrument's tip back on itself – for example to view something that would otherwise be hidden – requires a complex manoeuvre best undertaken by the computer.

It is also possible to use image analysis technology to give the robot complete autonomy. Just as doctors conducting a bowel examination use the view from the instrument's camera to guide their actions, so too can the robot. Image analysis can be employed to identify the centre of inside the colon and enable the computer to keep steering the tip of the instrument towards it. The robot would be instructed to pull the magnetic tip of the instrument to the far end of the colon; the operator would then take over, examining the image of gut lining while slowly withdrawing the colonoscope.

Inbuilt safety constraints prevent even the maximum strength of the magnetic field from moving the colonoscope with a force sufficient to damage the gut tissues. The magnetic field's strength is no greater than that already used routinely in magnetic resonance imaging (MRI scans).

EXPANDING ENDOSCOPES

Professor Valdastri's endoscopic ambitions are not confined to the colon. Aiming for an even more demanding target, he is also developing what he calls "magnetic tentacles" for reaching into the finest branches of the lung's airways. Just two millimetres in diameter, each soft and flexible tentacle has tiny, embedded magnets throughout its length. Its movement and conformation is determined by two robotically controlled external magnets able to set up and vary the complex magnetic field required to coax the tentacle along its assigned route.

Navigation in this case is dependent on a prior scan of the lungs, and will require a three-dimensional map. Having chosen a route to whichever part of the lung's interior is to be examined, a computer controls the movement of the external magnets, and so the tentacle's passage into the lung. By this means it should be possible to sample tissue from otherwise inaccessible depths of the organ, and to deliver treatments directly to those regions.

Professor Valdastri plans to make his colonoscopes disposable, thereby avoiding the need for the elaborate and costly cleaning required by the current, very expensive reusable instruments. The savings should more than offset the capital cost of the robotic arms. The intellectual property underpinning the system is licensed to Atlas Endoscopy, a company spun out of Professor Valdastri's laboratory. "The endoscope will be returned to the company," he adds. "We have planned a net zero approach. Plastics will be recycled, while electronics will be cleaned and reused." The simplicity of the controls will allow much of the procedure to be undertaken by staff with a nursing qualification.

Following initial testing on models of the human colon, the magnetically guided colonoscope has been demonstrated in animal experiments. These were conducted on pigs: a demanding choice since the pig colon is actually more convoluted than its human counterpart. The first trial on human patients is set for late 2023.

Open Bionics has provided two former Ukrainian soldiers with bionic arms, after they both lost an arm in the war

Improving home rentals: Tom Robins, CEO of data company **Switchee**, has been named Housing Digital Awards' 2023 Innovation Champion

Live sports audio company **Salsa Sound** was featured in a *Telegraph* roundup of the world-leading UK tech companies that power sports tournaments

HOW DOES THAT WORK?

MEMS SENSORS

When a car's airbags inflate in a crash, the decision to fire them stems from an array of devices embedded in the dashboard and doors, each barely larger than a grain of sand. Such devices are known as microelectromechanical systems (MEMS).

Detecting when a vehicle suddenly slows down to initiate airbag deployment was one of the first commercial uses of MEMS. Today, they're everywhere. Bosch, the market leader, started production in 1998 and has now made over 15 billion.

A typical new car will contain dozens, including MEMS on airbag duty, or monitoring tyre pressure and air conditioning. The accelerometers that detect when your smartphone's display should rotate from portrait to landscape are MEMS. So are the microphones embedded in AirPods that help separate the wearer's voice from the background. On board aircraft, MEMS gyroscopes can record aeronautical measurements that once required several kilograms of machinery. Countless other everyday technologies also rely on MEMS, from heart pacemakers to kitchen appliances.

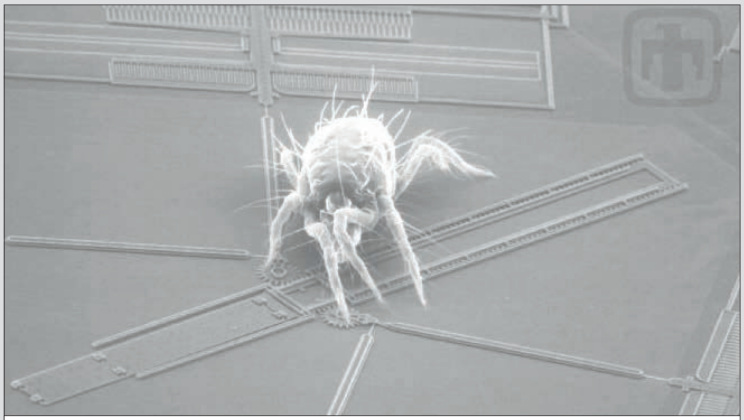
MICRO MACHINES

It's been almost 60 years since the first MEMS were manufactured. Semiconductor engineers capitalised on the manufacturing approaches developed for computer chips and used them to make these microscopic devices.

These days, MEMS are fashioned from silicon, polymers, metals or ceramics. Their internal parts, for example, a spring or weight, can be as small as one micrometre, with overall dimensions ranging from 20 micrometres to a few millimetres. High surface-area-to-volume ratios make them ideally suited to detecting marginal changes in magnetism, pressure, chemical composition, or temperature.

While their functions can differ enormously, what all MEMS have in common is their size and ability to convert electrical signals into movement, or vice versa. A MEMS sensor generates an electrical output when its components register changes in its surroundings, often by bending, stretching or contacting another part. On the other hand, a MEMS actuator converts an electrical input into mechanical movement.

So, what's actually happening inside? A MEMS sensor might contain a mass suspended between capacitive plates. When the suspended mass tilts towards one plate, it shows up as a change in capacitance. Movement of 0.0001° can be enough to trigger a reading on a tilt sensor. This type of device is known as a capacitive transducer.



A spider mite walking over a MEMS mirror assembly
© Courtesy Sandia National Laboratories, SUMMiT™ Technologies, www.sandia.gov/mstc

Often, the MEMS that come to mind are sensors, from accelerometers, microphones and gyroscopes, to devices detecting pressure and flow. However, MEMS can also work as switches and oscillators – for instance in communication systems. Meanwhile, micronozzles are common in inkjet printers.

BUILT TO LAST

While impressive in their own right, MEMS do not work in isolation. They must be bridged somehow with the outside world, typically by integration into electronic circuitry on a microchip. This also enables functions such as signal filtering or amplification.

MEMS – particularly sensors – often need some degree of access to their external environments. Yet they must also be packaged to protect them from contamination, for instance from dust, and some MEMS have to be hermetically sealed. Packaging also dissipates heat and offers their sensitive components protection from mechanical shocks and other unwanted physical stresses.

All of this is key when you consider the conditions MEMS often operate under: extreme temperatures, protective systems in vehicles crashing at high speeds, and being fired into space are just a few examples.

Where next for MEMS? The trend for even smaller wearable devices is likely to continue with them shrinking even further. Aided by MEMS, miniaturised hearing aids, precision drug delivery and noninvasive medical diagnostics could all be part of this future. Meanwhile, increasingly 'smart' autonomous vehicles will be kitted out with even more MEMS than cars today.