Ingenia

SEPTEMBER 2019 ISSUE 80

BIOELECTRONIC IMPLANTS
ROBOTIC WAREHOUSES
GROWING FOOD WITH SEAWATER
LIGHTER PLANE WINGS

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Front cover
Bombardier won the MacRobert Award in 2019 for its resin-infused advanced composite wing, currently used on the Airbus A220 aircraft. Using silicone, photographer Ted Humble-Smith created an image that reflects how the resin is injected into a vacuum within the carbon fibre wing, and is then heated under pressure to form the final shape © Ted Humble-Smith 2019

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EDITORIAL

LESSONS FROM GRAPHENE CITY

Scott Steedman CBE FREng

A decade on from the discovery of graphene at the University of Manchester in 2004, the city is becoming a world centre for research, development and product innovation in this exciting new field of materials engineering. Could Manchester become 'Graphene City' and provide the focus for a new industry? Earlier this year, the Graphene Engineering Innovation Centre (GEIC) opened for business on the university campus. The GEIC offers facilities and a team of engineers to support manufacturers scale up production and to accelerate commercialisation of this 'wonder material'.

Graphene can be manufactured as a powder or in flakes and can be used in so many ways. Blended or infused into, for example, insulation foam, rubber or a sheet of composite material, graphene can alter the strength, electrical conductivity or thermal properties of the host material. Graphene is already enhancing a wide variety of products from running shoes to aircraft wings.

It is, however, one thing to create these materials in a laboratory, but quite another to do it at factory scale. How will engineers design and make new products that benefit from graphene's special attributes? How can manufacturers store and transport blended and mixed graphene? How stable are the resulting materials? How can we test their properties? For small and medium-sized companies, it is expensive, time-consuming and risky to invest in their own facilities to answer these key questions, which is where the GEIC comes in.

The GEIC, led by industry, is modelled on Innovate UK's Catapult Centres. Like the Catapult Centres, the graphene centre provides factory scale facilities where large and small companies can experiment with production methods. The National Graphene Institute (NGI), a few hundred metres away, is a hub for graphene research. With over £200 million of investment committed to the NGI and the GEIC, more than 340 people work on graphene projects. Both bodies sit alongside the new home of the Henry Royce Institute, the UK's National Institute for Materials Science Research. Due to open next year, the 'Royce' already has a community of 900 academics and over £300 million of facilities.

The university's vision is that companies interested in commercialising graphene will come to Manchester from all over the world. In Graphene City they will have access to the knowledge they need, from world renowned researchers to production engineering experts, with facilities to match at every stage. Graphene City is a bold vision and could bring the best of UK science and technology research within reach of companies large and small. Six months after opening, the centre is already ahead of its plans to attract leading industry supporters.

The main difference between the GEIC and Catapult Centres is that the GEIC is smaller and focused on a specific industrial outcome, the commercialisation of graphene, rather than covering a broad area, as the Catapults do in fields such as high value manufacturing, 'future cities', or the digital economy. This focus should enable the GEIC to build a portfolio of projects that develop their own momentum. As the resident engineering teams develop their expertise, so will their ability to respond rapidly to new ideas.

Could the GEIC become a model for other universities, strengthening the ecosystem in the UK to support new and emerging technologies? Other leading universities, such as Sheffield, Warwick and Strathclyde, have also established similarly successful models for close engagement with industry. One key difference in Manchester is that the GEIC is building its in-house engineering team on an industry-style career path. In this way the GEIC's approach can avoid the employment constraints of PhD, post-doctoral or project-based hiring. There is more flexibility for short-term, rapid turnaround projects, which makes it easier for companies to try out new ideas.

The GEIC, building on the strength of the NGI and the potential of the Henry Royce Institute, could make a formidable contribution to the UK's innovation infrastructure. Other universities, institutes and research centres have their own success stories to share. Early engagement with engineers from industry is clearly one of the keys to success. The Royal Academy of Engineering is well placed to lead the community in promoting the benefits of industry and academia working together.

Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

STUDENTS CELEBRATE MARS ROVER

Students discovered that the rover will have a drill able to take samples up to two metres below the surface of Mars © Airbus

In May, Airbus invited students to its Mars Yard testing site as part of a series of events to celebrate its 50th anniversary.

Its Defence and Space division has been studying the geological environment of Mars and next year will launch a robotic vehicle to the planet to look for signs of life.

Students had the opportunity to see prototypes of the latest 300-kilogram Mars rover, which is named Rosalind Franklin after the DNA scientist. Students learned about the nine different experiments the Rosalind Franklin rover will use to look for life on Mars, had a go at programming a rover, and tested the model's functionality.

In 2003, the European Space Agency launched its first mission to Mars with the Airbus-built Mars Express satellite. The Rosalind Franklin Mars rover will take nine months to reach the planet and be capable of drilling as deep as two metres. The data collected by the mission will help evaluate the risks for future human expeditions and well as assist in broader studies of Martian geochemistry and environmental science.

The rover is expected to travel several kilometres during its stay on Mars and will have to endure temperatures varying from –130°C to around 5°C. The fluctuation can be nearly 100°C from day to night. Airbus plans to launch in July 2020, when the Earth will be aligned to reach the planet in the shortest timeframe.

ALAN TURING TO BECOME FACE OF £50 NOTE

In July, the Bank of England announced that the Second World War codebreaker Alan Turing will be the new face of the £50 note.

Turing has been credited with originating the field of computer science and his portrait will feature on banknotes issued from 2021 onwards. He is perhaps best known for leading the team that created the Enigma code-breaking machines during the Second World War at Bletchley Park. He subsequently played a key role in the development of the first computers at the National Physical Laboratory and the University of Manchester.

Mark Carney, the Governor of the Bank of England, announced the news in Manchester. He said: "As the father of computer science and artificial intelligence, as well as war hero, Alan Turing's contributions were far ranging and path-breaking. Turing is a giant on whose shoulders so many now stand."

The £50 note currently features the faces of the entrepreneur Matthew Boulton and James Watt. James Watt is a Scottish engineer and inventor whose improvements to the steam engine drove the Industrial Revolution. This year marks the 200th anniversary of his death and there are a series of events to mark the occasion.

© Bank of England

AWARDS FOR TOP INNOVATIONS AND ENGINEERS

Young Engineer winners (l–r): Dr Mariia Sorokina, Dr Áine Ní Bhreasail, Dr Giorgia Longobardi, Sophie Harker and Rosie Goldrick

In July, the Royal Academy of Engineering hosted its annual Awards Dinner to celebrate and recognise engineers who have made a remarkable contribution to the industry.

The event celebrated the 50th anniversary of the MacRobert Award, the UK's longest running and most prestigious national prize for engineering innovation. Bombardier won the award for its innovative, resin-infused advanced composite wing (see page 28). The other three finalists were Darktrace, for its AI-powered 'self-healing' cybersecurity system that can both identify and neutralise cyberattacks; M Squared, whose sapphire laser produces the world's purest light, enabling new scientific discoveries; and OrganOx for creating a device that can keep a human donor liver functioning outside the body for up to 24 hours prior to transplant.

The Rooke Medal was awarded to European Space Agency astronaut Major Tim Peake to mark his inspirational promotion of engineering and space through the Principia mission's education programme, the largest and most successful educational campaign supporting a European astronaut mission.

The RAEng Engineers Trust Young Engineer of the Year awards, established with the support of The Worshipful Company of Engineers, were presented to five women engineers. One of the winners, Rosie Goldrick, an Engineering Director at MASS, also won the Sir George Macfarlane Medal for demonstrating outstanding excellence in the early stage of her career.

The engineers behind the Shah Deniz 2 project, delivering gas from Azerbaijan to Europe direct for the first time, received the Major Project Award for their work in delivering the complex offshore, onshore and pipeline gas development project. It will help Europe satisfy its future energy demand and play a major role in the continent's transition to a lower carbon economy by providing more than 10 billion cubic metres of gas per year.

SMART LOCKERS FOR MEDICINE WINS AFRICA PRIZE

Neo Hutiri, a 31-year-old South African electrical engineer, has won the Royal Academy of Engineering's 2019 Africa Prize for Engineering Innovation.

Hutiri and his team developed Pelebox, a smart locker system designed to dispense medicine to patients with chronic conditions. It is used at public healthcare facilities in South Africa, cutting down queues and easing pressure on the healthcare system.

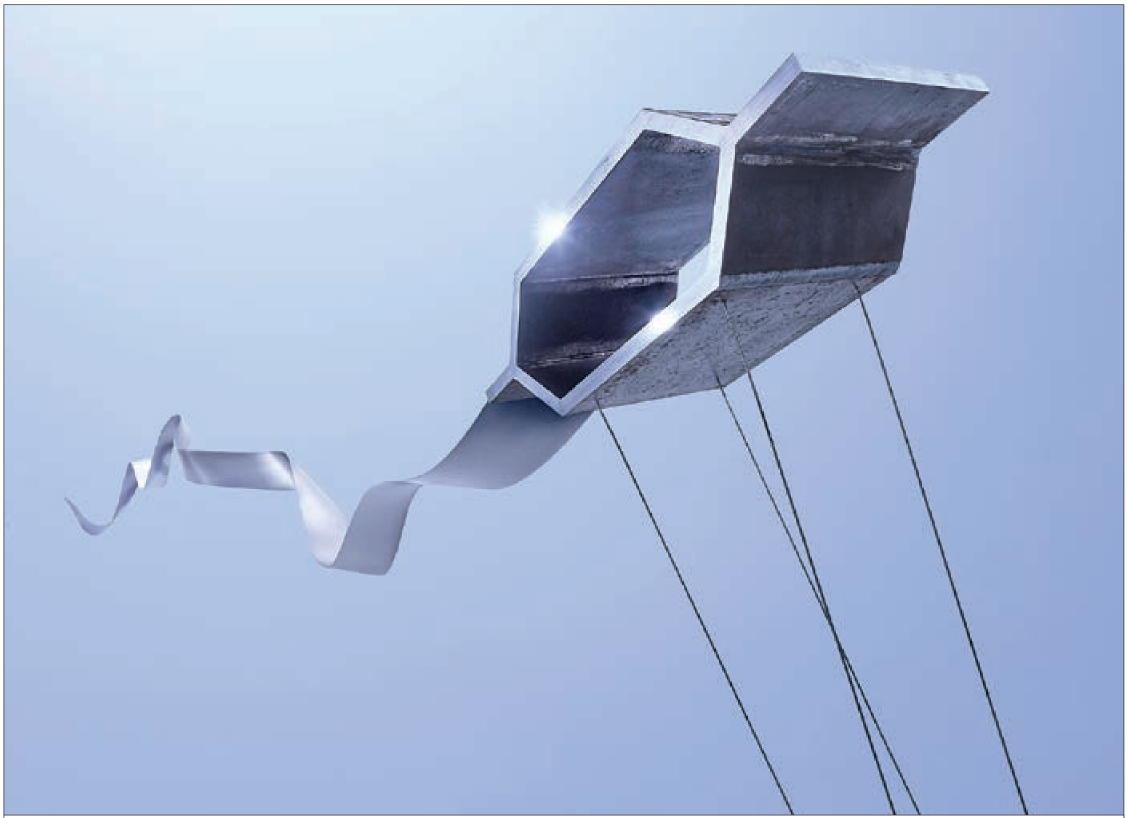
Pelebox is a simple wall of lockers, controlled by a digital system. Healthcare workers stock the lockers with prescription refills, log the medicine on the system, and secure each locker. The patient is then given a one-time PIN to open their locker and access their medicine. It gives patients access to their medicine within 36 seconds, in contrast to the average 3.5 hours it takes in other healthcare facilities. This is significant in South Africa, where more than 4.7 million patients collect monthly treatments from public clinics.

"Pelebox will improve healthcare for everyone using and working in a severely strained public healthcare system," said Africa Prize judge, John Lazar.

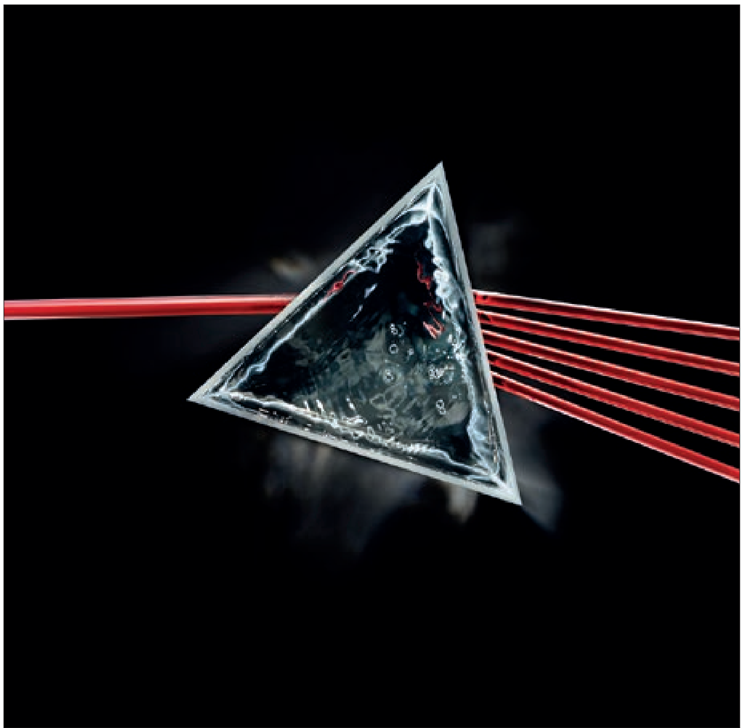
The Africa Prize, founded by the Royal Academy of Engineering, is Africa's biggest prize dedicated to engineering innovation, with a £25,000 cash prize. Now in its sixth year, it encourages talented sub-Saharan African engineers to develop innovations that address crucial problems in their communities in a new and appropriate way.

Neo Hutiri's smart locker cuts down queues for collecting medicines

CELEBRATING 50 YEARS OF THE MACROBERT AWARD



The Severn Bridge © Ted Humble-Smith



Cobalt Light Systems (now Agilent) © Ted Humble-Smith

The Academy commissioned photographer Ted Humble-Smith to create conceptual images celebrating the 50th anniversary of the MacRobert Award.

Ted Humble-Smith uses his imagination and technical expertise to produce vibrant images that push the boundaries of commercial photography. He talked to engineers involved in MacRobert Award-winning projects to picture the concepts behind the innovations. His images capture the thought process behind the breakthroughs, rather than illustrating the innovations' technical workings.

For his image of the Severn Bridge, joint-winner of the first MacRobert Award in 1969, Ted talked to Michael Parsons FREng who worked on the project. The Severn suspension bridge was a groundbreaking idea based around the structural integrity of a plated steel box. It replaced the traditional lattice work construction of bridges, which came under scrutiny after the Tacoma Narrows suspension bridge disintegrated. Mike's plated steel hollow box construction was aerodynamically favourable to wind forces hitting the bridge side on, splitting the airflow above and below the deck.

The aerodynamic box structure reminded Ted of a kite with a tail, which would demonstrate both the problem and the solution that was used to design the deck. He created a steel-framed box kite, similar in design to the cross-section of the bridge, and photographed it 'flying' with a steel tail flapping around behind it in a similar form to the oscillation that destroyed Tacoma.

To illustrate the 2014 winner Cobalt Light Systems (now Agilent), Ted talked to one of its inventors, Professor Pavel Matousek FREng. Cobalt developed a system that could identify liquid in a sealed container within seconds, perfect for airport security. The same technology could confirm the identity and perform batch release of pharmaceutical raw materials. It relies on a technique called Raman spectroscopy – a pattern of light is formed that is uniquely dependent on the content of the liquid, and a single substance or multiple substances can be identified. Ted made a prism out of liquid and coloured rods used to signify the lasers.

GET INVOLVED IN ENGINEERING

BRISTOL OPEN DOORS
13 TO 15 SEPTEMBER 2019

Explore Bristol through talks, workshops and expert-led tours that highlight some of the Bristol's most inspiring civil engineering.

www.bristolopendoors.org.uk

TECHNIQUEST GLYNDŴR
21 AND 22 SEPTEMBER 2019

Celebrate the unique engineering heritage of the Pontcysyllte aqueduct and canal, which this year marks 10 years as a UNESCO World Heritage Site.

bit.ly/2TxJWae

NEW SCIENTIST LIVE
10 TO 13 OCTOBER 2019

New Scientist Live returns to London's Excel, with five zones exploring the most exciting elements of the cosmos, Earth, humans, technology and engineering.

The Royal Academy of Engineering stand will showcase the *This is Engineering* campaign, with engineers demonstrating how they turned their passions into engineering careers.

Ingenia readers can get a 10% discount on tickets by using the code RAE10.

live.newscientist.com

NORWICH SCIENCE FESTIVAL
18 TO 26 OCTOBER 2019

Norwich Science Festival returns for October half term with nine days of exhibitions, shows and hands-on activities for all ages and all levels of knowledge. The Explorium zone features free activities themed around food and health, zoology and mammals, and engineering and technology.

www.norwichsciencefestival.co.uk

THIS IS ENGINEERING DAY
6 NOVEMBER 2019

A day dedicated to publicly celebrating the engineers and engineering shaping our everyday lives and the world around us. This year, it focuses on challenging the stereotype of engineers and showcases what 21st century engineers and engineering really look like.

www.thisisengineering.org.uk

© Institution of Civil Engineers

WATER – FROM SOURCE TO TAP
RUNS TO FEBRUARY 2020

This exhibition explores the hidden depths of water engineering and the work of behind-the-scenes heroes, who fight fatbergs, flooding, and save lives through the provision of clean water and sanitation. Explore the zones within the exhibition, watch films, explore virtual reality worlds, and have a go at building civil engineering models in the activity zone with Lego and building kits.

www.ice.org.uk

HOW I GOT HERE

Q&A

NATALIE CHEUNG
CIVIL ENGINEER AND STEM AMBASSADOR COORDINATOR

Natalie Cheung is a STEM Ambassador Coordinator in London. She recruits and trains volunteer engineers to engage with young people through hands-on activities, careers events and mentoring. Natalie was a STEM Ambassador herself while working as a railway civil engineer.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

I was inspired by the film *I, Robot* and became very interested in artificial intelligence, computer science and technology. That was my gateway to considering engineering as a career. After exploring the engineering disciplines, I applied to study civil engineering at university. This was largely inspired by a week's work experience at a construction project management firm when I was 16. Without this experience, I would never have heard of civil engineering. I was really lucky to meet people involved with cost management, project management, architecture and different engineering areas, which taught me why these roles are important for the built environment.

HOW DID YOU GET TO WHERE YOU ARE NOW?

I was good at maths at school, which seems like a very common story for engineers. I hope that engineering industries will open and promote more opportunities for young people even if they are not confident about maths! I chose maths, computing and physics for my A Levels, with Latin and further maths at AS Level. I went on to study civil engineering at the University of Manchester and that's when I first started volunteering as a STEM Ambassador. I organised a student-led group that ran robotics workshops with female pupils across Manchester and Yorkshire. I was also fortunate enough to gain experience working at Crossrail's Farringdon Station site during my summer holidays. This opened my eyes to the opportunities for civil engineers in the transport sector.

After university, I completed my graduate development training at AECOM in their railways team. I worked on the access points that allow maintenance staff and vehicles to get to railway tracks. I also helped design a new train station in Kent! My favourite project was for works related to HS2 and London Euston station, for which I was a deputy project manager. HS2 is a huge rail project to connect London with Birmingham, Manchester and Leeds and I am excited to have played a small part in this massive collaborative project.

While working at AECOM, I also took a year-long sabbatical to volunteer overseas and travel. As part of my voluntary work, I supported a solar energy enterprise in Zambia to provide power to rural communities. This opened my eyes to more opportunities to use my engineering skills – the options are limitless. After my sabbatical, I became an AECOM corporate social responsibility representative alongside my role as civil engineer. I'm so passionate about the benefits of volunteering and bring that enthusiasm to my current role at STEM Learning.

WHY IS IT IMPORTANT TO INSPIRE THE NEXT GENERATION?

There are a lot of misconceptions about careers in engineering. Some people believe you need to be super brainy and high-achieving in maths to be an engineer. Others think that engineering jobs are too dangerous and dirty. It's important to bust these misconceptions to ensure that young people, as well as their parents and teachers, know the opportunities that are open to them in engineering. I love working with different engineering employers to get engineers engaging with young people. I meet people in a wide range of roles, some in sectors that I never knew existed. Not only does this raise aspirations for more diverse people to join the industry, but it will also help build the future talent pipeline to fill the expected skills shortage.

In 2018, Natalie led a team of British and Togolese young people to deliver a government-funded project with the charity Y Care International. She was later awarded the University of Manchester's Medal for Social Responsibility and Alumni Volunteer of the Year 2019. She is pictured with Dame Nancy Rothwell DBE DL FRS FMedSci, Vice-Chancellor of the University of Manchester © Mark Waugh

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

Engineers work in teams and solve real-world problems! I love being part of engineering committees that are pushing for progress, whether that's in safety, inclusion, or professional development for example. Engineering creates solutions for all people so I hope to see real intersectional diversity and inclusion in the future.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

I'm office-based but spend about half the week in other people's workplaces. A key part of my job is to manage relationships with our partners. They could be councils, companies, schools, professional engineering institutions, or government departments. I attend events to promote the STEM Ambassador scheme and support companies to develop their STEM outreach programmes. My favourite part of the job is delivering communication and engagement training to STEM Ambassadors so that they are ready to engage with young people.

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

You probably already have a lot of the skills that you need to be an engineer. Search online for opportunities to use them. If you can get any experience of an engineering workplace while still studying, make the most of it. Nothing can beat seeing a real engineering workplace in action.

WHAT'S NEXT FOR YOU?

With other members of the Women's Engineering Society London Cluster, I helped organise our first work shadowing campaign this summer. We want to provide opportunities, like the one I had, for more female students to gain experience of engineering workplaces. We hope to break down one of the barriers to joining the industry and grow our work shadowing campaign for next year.

This summer, I also attended the BIG Event, a STEM communicators conference on a bursary award. I hosted a panel discussion and received public speaking training from the TED team in the US. I want to build on these public speaking experiences, and apply what I've learned about public engagement.

Maybe my job title will include 'engineer' again, who knows?

QUICK-FIRE FACTS

Age: **25**

Qualifications: **BEng (Hons) Civil Engineering, University of Manchester. Currently working on a Chartered Management Institute qualification.**

Biggest engineering inspiration: **Seeing people of all ages and backgrounds use the tube in London everyday.**

Most-used technology: **Spotify for music and podcasts. Spotify knows that I'll like a song before I've even heard it!**

Three words that describe you: **Motivated, perceptive, energetic.**

OPINION

AI IS NOT MAGIC BUT IT IS COMPLEX

People who use AI need to trust the technology and how its data is generated. Mandy Chessell CBE FREng, an IBM Distinguished Engineer, looks at the ethical responsibilities for engineers developing the technology and what legal and governmental frameworks that still need to be established.

Mandy Chessell CBE FREng

Artificial Intelligence (AI) is software that uses data to make decisions. The controversy surrounding it comes with its complexity. It typically operates with many sources of data, using complex logic that is hard for a human to understand or explain.

The digitisation of core infrastructure and services opens up many new opportunities for the use of AI in all aspects of our daily lives. As engineers we will be faced with the question of whether it is ethical to use AI in the systems we build, and our reputations will be won or lost on the future outcomes of these decisions.

In the Statement for Ethical Principles, updated by the Royal Academy of Engineering and the Engineering Council in 2017, there were four fundamental principles to adhere to. These came under the categories: honesty and integrity; accuracy and rigour; leadership and communication; and respect for life, law, the environment and public good. These principles provide a solid foundation on which to build new engineering practices.

Technologies in general are not inherently ethical or unethical. It is the use that we put them to that determines whether a particular engineering system is ethical or not. AI is no exception, but as an engineer considering embedding AI into a system, it is necessary to step a little deeper into the technology to understand where the ethical risks occur.

AI is not a single technology. It is an assembly of technologies. At its centre is the AI decision-making logic, which works on an optimised store of knowledge based on the data that it has been exposed to. This decision-making logic is fed data about the current status and then produces a result that is acted upon in some way. If it is in an actively learning mode, then the result, and the outcome or change in the situation, is fed back into the decision-making technology to improve its knowledge store and hence the accuracy of future decisions. Around the decision-making logic are the components that capture and assemble the input data and act on the output decisions. Any one of these surrounding components can have as much effect on the outcome of the AI systems as the decision-making logic at the core.

An AI project team must determine the impact and the scope of that impact on the individuals and society affected by the AI system's decisions. This will establish the level of quality that is needed in the decision-making process and any additional support that the system must provide.

For example, consider the use of AI to choose which travel destination to feature on a travel booking website. The impact of a bad choice on the individual using that website is usually minimal and short term. However, what about a scenario where AI is assisting a doctor in a medical diagnosis or assessing people for jobs or mortgages? Any resulting decision is likely to have a significant and long-term effect on the individual under consideration.

With this focus in place it is possible to specify the minimum level of accuracy that is required. This will then decide how to validate results, the explanation and consent needed from the individual, the circumstances under which a human decision-maker needs to be involved, and any mitigation management that needs to be in place if the decision is wrong.

Once the necessary accuracy of the decision-making is determined, the team need to consider what data can be practically (and legally) fed into the decision-making process when the system is running. This will include the scope, accuracy, precision and access speed of the data. This may be stored data or data that is being generated live within the system (such as data from sensors). We then need to decide whether this data is sufficient to drive the accuracy needed.

AI must be trained with real-world data. It is important that the profile of this data matches the profile of data that is to be fed into the system when it is live. Without this, the results may be biased or just plain wrong. It is the responsibility of the engineering team to verify the training data whether they are training the AI themselves or bringing in a decision-making model from a third party.

AI technologies operate in a pipeline where raw data supplied to them is transformed into a format that is efficient for the decision-making logic. This transformation may reduce the precision or filter values from the incoming data and hence be making decisions on a smaller set of data than is expected. If, for example, in the case of image recognition, the transformations are lowering the definition of the incoming images to speed up the decision logic, it has to be determined whether this will materially impact the quality of the results below the bar needed by the rest of the system.

Since the world is constantly changing, so is the data that is produced. Whether the AI model is using feedback from its decisions to dynamically improve its accuracy or if it is operating in a consistent mode, it will need constant monitoring and updates to correct any bias or obsolescence that may be creeping in.

Finally, data from the system may be fed into other systems. This secondary usage may be planned and managed, or unplanned due to leakage or theft of data. The engineering team has a duty of care to safeguard the system components and data flowing through it, to ensure it cannot be raided or misdirected by third parties.

Much of this activity is already considered and carried out for complex physical components in engineering projects. AI is not magic, but it is complex. As engineers, we need to apply and evolve the standards we use for complexity in the physical world for the digital world. We need to ensure that our digital systems are operating in the ethical way that was intended.

To underpin the use of AI in engineering we need clarity from government or law on data ownership. This is especially important when new data is derived from multiple sources and the scope of liability when it comes to data supplied for decisions. This will help to clarify responsibility for a correct result and it may evolve though regulation or best practice.

Open standards for data contracts and their associated terms and conditions are critical as the basis for automatic enforcement and auditability. This needs to be a part of an open metadata and governance ecosystem that supports and manages digital systems.

There is also a need for standard data set definitions representing the minimum requirements for data that is used for specific type of decision. For example, there are standards for the type of aluminium that can be used for building aircraft – so there should also be standards for the quality and content of weather and other type of environmental data used by air traffic management.

It is time to take the engineering of data in the digital world as seriously as we take the use of raw materials in the physical world. To make great engines you need quality parts. AI algorithms are the engines of the future – so let's get focused on the standards and methods that will ensure they deliver on their promise.

BIOGRAPHY

Mandy Chessell CBE FREng is an IBM Distinguished Engineer, Master Inventor and Fellow of the Royal Academy of Engineering. She leads the ODPi Egeria open source project and is a trusted advisor to executives from large organisations, working with them to develop their strategy and architecture relating to the governance, integration, and management of information.

A SQUARE PEG IN A ROUND HOLE

A render demonstrates how 22 Bishopsgate dominates the City of London's earlier tall buildings, including 122 Leadenhall Street – The Cheesegrater – just to the building's left, with The Shard across the River Thames to the south © 22 Bishopsgate

22 Bishopsgate is the tallest building in the City of London and the second tallest in western Europe. However, the most extraordinary feature of this new skyscraper is not its sheer size, but the ingenious structural engineering – or 'structural gymnastics' as the team describes it – that has enabled the remains of an earlier, failed development to be transformed into a large efficient modern office block. Hugh Ferguson talked to Peter Rogers CBE FREng, co-founder of the project's developer Lipton Rogers Developments, about the building's innovative engineering.

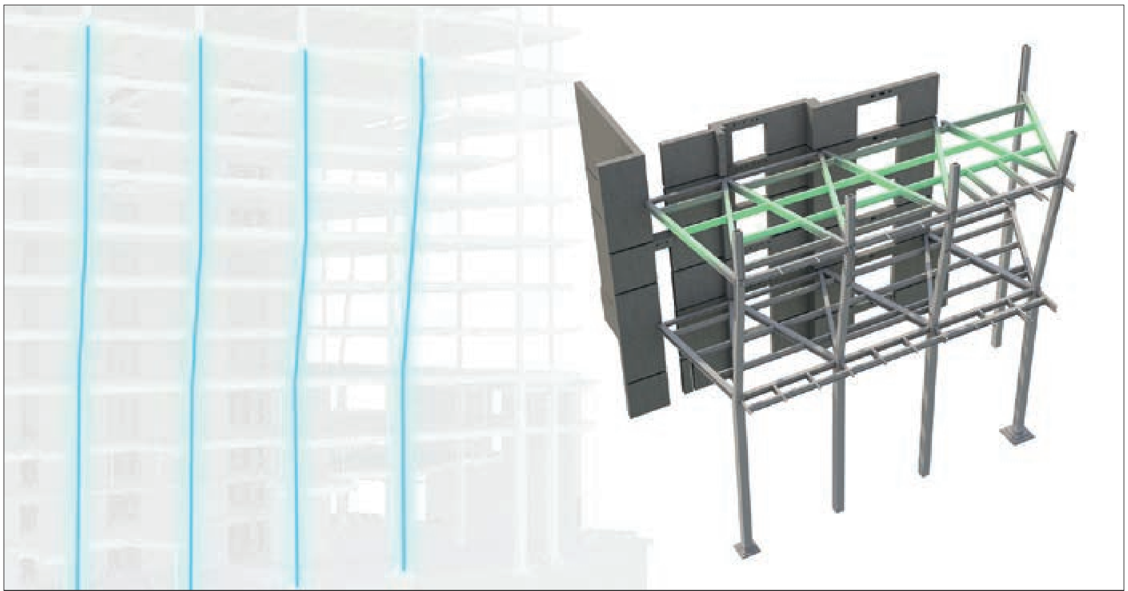
Modern high-rise work spaces in the City of London have led to a succession of instantly recognisable iconic structures with quirky nicknames – 'The Gherkin', 'The Walkie-Talkie' and 'The Cheesegrater'. The tallest and most eye-catching of all was set to be 'The Pinnacle', a twisting, tapering tower, provisionally nicknamed The Helter Skelter. However, following the 2008 property crash, the investors pulled out and the project stopped. By then London's deepest piles had been sunk, most of the three-storey basement had been built and the first seven stories of the building's concrete core had been erected above. Efforts to revive the scheme came and went, and the desolate, abandoned concrete soon acquired a new nickname: 'The Stump'.

Although widely admired as an architectural masterpiece, The Pinnacle had severe drawbacks. It was inefficient and expensive to build: its tapering, spiralling shape allowed little opportunity for repetition in construction with its highly complex engineering and irregular floor spaces. Also, post-2008 developers wanted efficient buildings, attractive to both businesses and their employees, which would help draw activity back into the City. A very different building was required, one that used the size and shape of the plot more efficiently, and was affordable to build.

The challenge was taken up by Lipton Rogers Developments (LRD), with its architect PLP, engineers WSP and contractor (as for The Pinnacle) Multiplex. LRD had jointly run an exercise with the City on how to construct high-rise buildings quicker and cheaper, and this was a chance to put the exercise into practice. The challenge was to create a building the same height as The Pinnacle, but with a third more lettable space, no more weight and at less cost.

BUILDING FOUNDATIONS

The basic design of the new 62-storey block, provisionally dubbed Twentytwo, is conventional by modern skyscraper standards: a large central concrete core holding the lifts, steel columns and beams around the periphery and concrete floors in between. The difficulty came at the bottom. The columns and core were not in the same place as The Pinnacle's existing piles. Installing new piles would be expensive and would delay the start of construction by many months.



Columns along the west edge of the building slope inwards between levels six and three, with the huge horizontal forces countered by horizontal trusses connecting the columns to the concrete core © WSP

The core of the old stump had to go, but much of the existing basement and all the old piles could be re-used. This required a series of engineering measures to transfer the huge loads from the core and columns of the new building on to more than 300 existing piles – 25 mega-piles installed for The Pinnacle plus other smaller piles from previous developments – using their bearing capacity to the full without overloading any. In the end, engineers only needed 85 new piles, most to lend support to the larger concrete core, and these were small enough to be sunk with a small piling rig that could fit inside a basement storey.

In many places, the transfer of load to the existing piles was achieved by installing massive beams within the basement area – effectively one-metre-thick reinforced concrete walls up to three storeys high. However, along the west side, the huge loads from the peripheral columns had to be brought in to the piles located much nearer to the central core. Engineers could

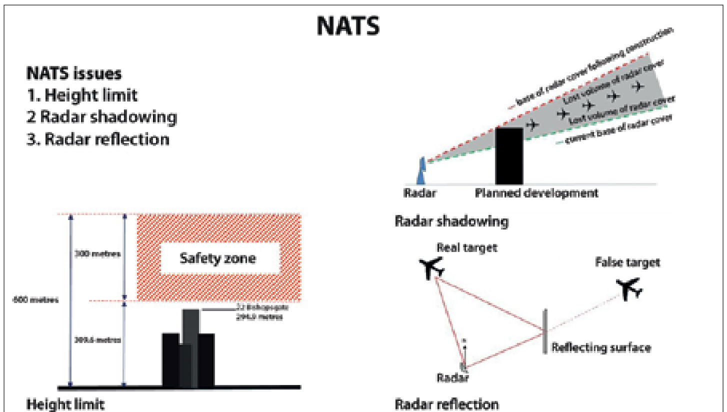
AIR TRAFFIC CONTROL

Structural engineers rarely get involved with air traffic control, but a very tall building under busy flight paths is an exception.

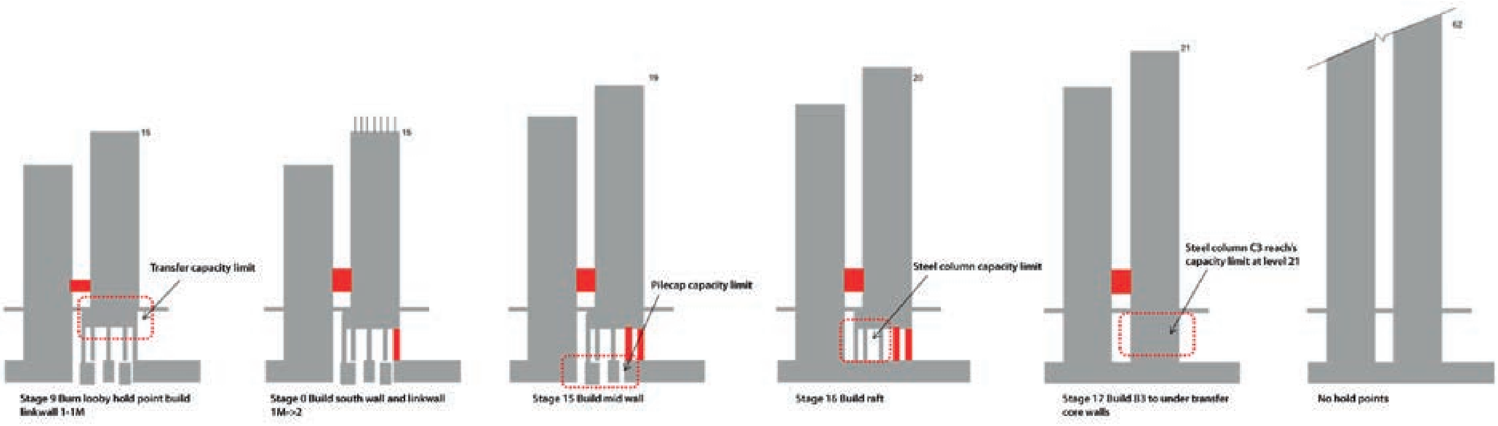
The flight path to London City Airport is directly over the City of London, with planes normally at more than 600 metres but with a safety zone down to 305 metres to allow, for example, for failure of a plane's engines. The building was designed to fit within this limit, but the designers had assumed that cranes would be allowed to rise higher during construction – as was the case with The Shard across the river to the south ('Building The Shard', *Ingenia* 52). When planning permission came through with a surprise 309.6 metre limit on crane height, a quick redesign of the top of the building and how it would be assembled was required, with the topmost crane only allowed to operate with its jib horizontally. Eventually through negotiation, the restriction was lifted outside flying hours so that the jib could be raised – between 11pm and 6am Monday to Saturday and all day on Sundays. A 'hotline' was installed with City Airport so that the site could check that all flights had stopped before they lifted the jib, and to confirm that the jib was locked down before flights could restart.

The flight paths in and out of Heathrow are at a much higher level, but the issue here was interference with the radar operated by Britain's air traffic control service NATS – either shadowing, which would hide some aircraft, or reflection, which would cause aircraft to appear on the radar in the wrong place. An impossibly low height limit was imposed on the building until a solution could be found.

LRD quickly identified that the 112-metre-high 1960s Hyde Park Barracks was directly in line between the NATS radar station at Heathrow and Twentytwo, thereby casting its own shadow. This allowed the height restriction to be raised to the top of the 'shadow', at 126 metres, which bought time for a long-term solution. LRD worked with NATS to create software effectively cross-referencing readings from two separate radar stations to eliminate the risks.



Air traffic control issues show the safety zone for London City Airport approaches, which limited building height to 309.6 metres, and the effects of shadowing and reflection on NATS radar © Lipton Rogers Developments



Sequence of 'top-down-bottom-up' construction for the south core, showing the additional strengthening measures to allow the core to be increased to level 20 before the foundations below were completed © WSP

do this by sloping the columns inwards from level six to level three, returning to vertical for the entrance lobby down to ground level, and then sloping again from ground to basement three. Sloping introduced massive horizontal forces that pushed outwards at the top of the sloping column and inwards at the bottom. To resist these, large steel Warren trusses (steel members arranged in a triangular grid) were installed in a horizontal plane just beneath the floor to connect the line of columns with the solid concrete core – a truss at the top of the sloping column to take the tension and another at the bottom to resist compression.

For one of the columns near a corner of the building, the truss solution would not work for the tension, so instead the top of the sloping column was anchored in to the core with an array of high-strength steel cables, sheathed and embedded in the concrete floor and then made tense.

Site constraints created other challenges. The old basement included two lorry lifts, which was the main means of access to the lower levels during construction and not easy to relocate, so the structure above had to bridge over it. Engineers designed a 'mega truss' to transfer the load from three of the main columns to the pile caps via columns either side of the lift. Elsewhere, basement space was needed for delivery or waste-collection lorries to turn, requiring one column to be removed. A massive 15 metre-long, 3.8 metre-deep, 97-tonne steel 'mega girder' was inserted just below the ground floor slab to transfer the load to points where there was sufficient pile capacity.

The north side of the new concrete core sits over the adequate foundations of the old core, but the south side required new piles and a new heavy concrete raft to be constructed first. The solution here was to adopt 'top-down-bottom-up' construction. A massive grillage of columns and beams was assembled in basements one and two to support up to

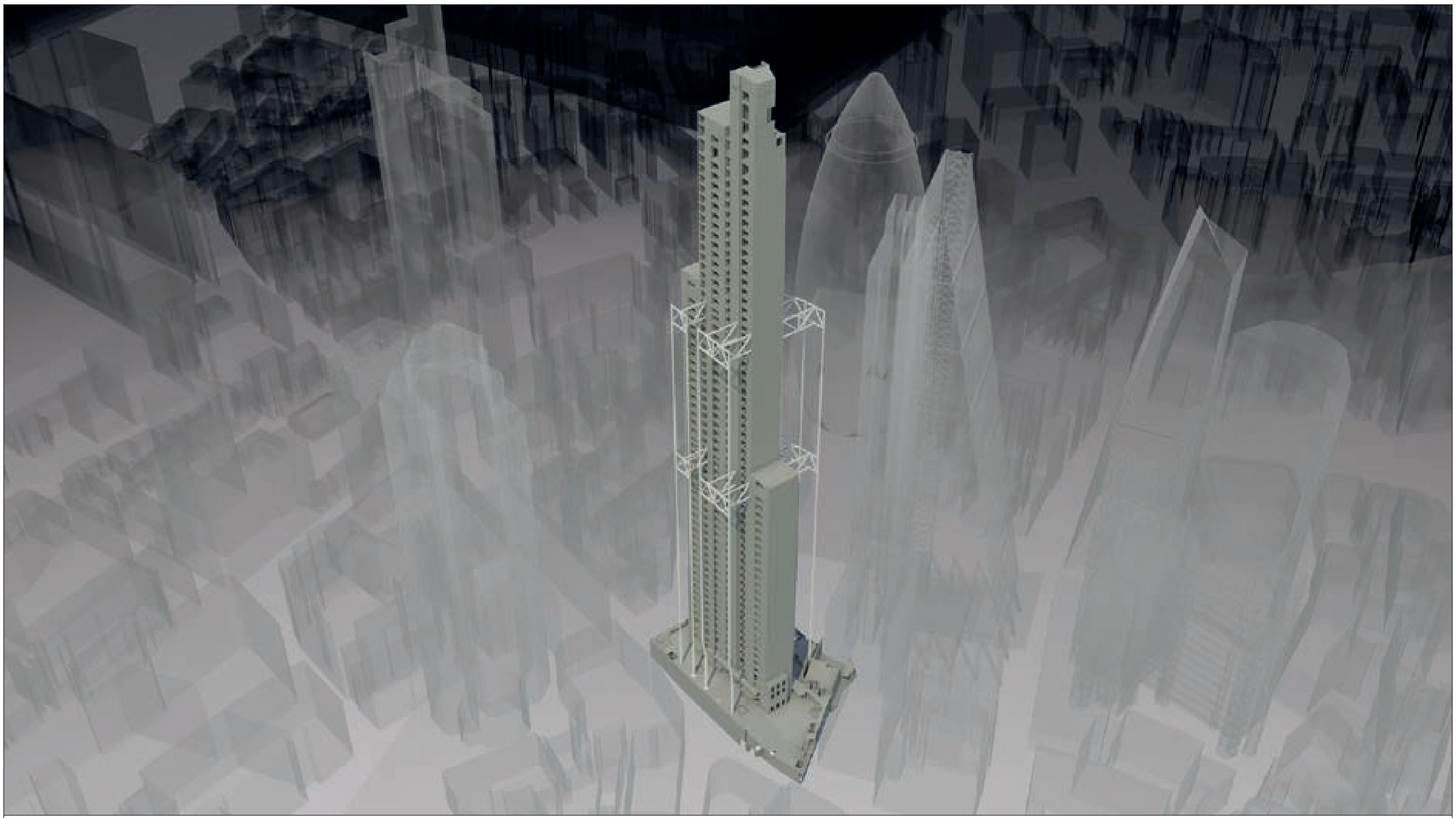
FIRE SAFETY

Twentytwo has all that would be expected in terms of fire safety in a modern tall building, including careful choice of building materials, compartmentalisation to prevent fire spread, a fire-engineered structure to allow at least a four-hour safe period for evacuation, smoke control, four dedicated lifts for firefighters and a conventional 'down-the-stairs' evacuation procedure. But, as a first in the UK, the lifts will also convert in a fire to 'vertical tube trains' for rapid evacuation.

When the external cladding of the Address Downtown tower in Dubai caught fire in 2015, the remainder of the building's fire safety strategy worked well enough to prevent serious injuries – apart from one person who suffered a heart attack during the evacuation. Hurrying down some 60 flights of stairs can be exhausting for fit people, and with the UK population getting less fit, using the lifts makes sense. However, this is usually ruled out as too expensive: using lifts in fires requires fire-rated shafts, dual power supply, cars pressurised against smoke ingress and large lift lobbies free of flammable material.

LRD's ingenious solution has avoided these costs. The building is divided vertically into zones, with fire-hardened floor slabs with a two-hour fire rating separating them at levels 26, 42 and 58, which coincide with the levels served by each of the groups of lifts. Each set of lifts has a motor room just above the fire-hardened slab, itself encased in concrete.

A fire on the lower floors will still require a conventional evacuation, but if a fire is detected at a higher level, lifts will spring into action to evacuate people from floors up to the nearest fire-hardened slab beneath the fire. LRD estimates that the top three floors could be evacuated in just 20 minutes, a third of the time it would take if everyone used the stairs.



The concrete core containing lifts and providing the primary means of stability for the building, showing the two-storey high steel outriggers at levels 25 and 41 and vertical steel 'belts' embedded in the facade to limit sway. The core gets smaller nearer the top, as some of the lifts serve only lower floors © WSP

15 storeys of core above. This left basement three free for work to continue on the foundations beneath – with everything above supported on just four columns. As construction of the core proceeded faster than the foundations, the contractor asked if the grillage could support another six stories of core: this was achieved with additional strengthening and temporary columns, and by the time the core reached 21 storeys the new foundation was complete and the temporary grillage could be dismantled.

STOPPING SWAY

For wind loading, the design to avoid toppling is straightforward: the real challenges are to limit sway to levels that occupants do not find disturbing, and to avoid the 'windy city' effect of creating strong currents of air around the building, particularly near ground level. Engineers carried out extensive modelling and computer simulations, involving Formula 1 expertise in computational fluid dynamics.

The building itself and its concrete core are roughly rectangular and movement along the long edge was not an issue. To limit sway along the short edge, where the width of the concrete core is only 14 metres and the orientation causes greater wind loads, double-storey outrigger steel trusses were installed at levels 25 and 41 between the core walls and the periphery, where they were connected to the columns.

Concrete shrinkage, compression of concrete and steel under load, and settlement of piles all lead to significant movement in such a tall, heavy building. Movement differs significantly between the concrete core and the peripheral steel columns: 60 millimetres in total for the concrete and 200 millimetres for columns where the stresses are greater. This movement was anticipated and dimensions adjusted accordingly, but it meant that bolts connecting the outriggers to the structure could not be tightened until after the building had been 'topped out' in May 2019.

Meanwhile near ground level, the complex array of baffles developed through modelling and computer simulation to create a wind-free environment have been neatly integrated with artwork, so that they appear creative rather than merely functional. LRD's vision for 22 Bishopsgate was to create a community rather than a collection of standalone tenancies – a 'vertical village' of some 13,000 people – and most of the design features of the building stem from this vision: higher ceilings and full-height glazing for natural light; hassle-free entry and lifts; common amenities, such as London's largest bicycle park in the basement, plus a communal food hall, an external terrace, a business club, a wellness centre and gym, a relaxation zone and an innovation hub, to help improve work/life balance; flexibility for tenants to create their own space and to allow for future changes of use; and a state-of-the-art technological backbone that is a first for a new building in the UK [see *A Smart building*].

BIOGRAPHY

Peter Rogers CBE FREng is Co-Founder of Lipton Rogers Developments. He is an engineer and property developer specialising in delivering complex building projects, working with government and industry to improve environmental and working practices in construction He was awarded a CBE for services to construction in 2007, is a Fellow of the Royal Academy of Engineering and the Royal Society of Arts, and an Honorary Fellow of the Royal Institute of British Architects.

A SMART BUILDING

Twentytwo will have some of the smartest technology yet seen in a large building, helping to control the building services and provide a higher level of service to tenants and workers.

All office buildings have some form of building management system (BMS) linking and controlling the heating, cooling and electrical systems. The BMS at Twentytwo is large-scale, reflecting the size of the building, but the innovation lies in an overarching smart building platform (SBP), created with automation software provider Iconics, which collects and analyses data from the BMS and other systems in the building. With half a million sensors on the BMS alone, the amount of data is enormous and the opportunities for applying artificial intelligence to analyse and utilise this data are many and varied.

At a simple level, this helps optimise energy use. The SBP may also, for example, learn over time that failure of a fan on a chiller unit is usually preceded by a characteristic change in vibration of the unit: it can then spot the vibration change, order a new part and generate a work order for replacement before the unit fails. On a larger scale, this could eliminate all unexpected equipment failures, and do away with regular, planned maintenance – improving quality and reducing maintenance costs. Or the system may spot that sales of a particular item in a catering outlet spike when the weather is humid: data from the weather station located at the top of the building can then advise the caterer when to increase stocks of that item.

The system is also linked to the 9,000 blinds installed within the sealed triple glazing of the building's full-height windows, to limit both heat gain and glare. The blinds are normally fully open, but are lowered automatically depending on the intensity of sunlight, detected from the weather station, as well as by the temperature in the room. An integrated 3D model of surrounding buildings allows the system to adjust blind heights for shadowing and for reflected solar glare.

The control software for the lifts is also linked into the system. For example, if the system is forewarned of many visitors arriving, it can order additional reception staff and ensure that the right lifts are in place on time to take the visitors to their meeting. In case of fire, it can automatically switch the appropriate lifts to evacuation mode.

A facial recognition system – faster and less intrusive than those often found at airports and never before used on this scale – replaces security checks for regular staff, making entry to the building a seamless process. It also provides a live record of who is in the building.

Tenants can be provided with almost any information they ask for. They can set their own heating and cooling controls, but then be informed of their energy consumption with suggestions for improving efficiency. At a more innovative level, data from movement sensors used to control lighting, linked to IT data on time and place of each person's log-on, can be used to identify parts of their floor that are underused, or reveal how well Team A on one side of their floor is integrating with Team B on the other.

The system will also allow the building's sustainability credentials – for the building as a whole or just a tenant's area – to be monitored in real time, not just the one-off measure required by conventional certification systems.

Besides a BREEAM Excellent sustainability credential, Twentytwo was the first big UK building to be registered for the WELL Building Standard, which focuses on how buildings can enhance, rather than compromise, people's health and wellness. This helped drive the high ceilings and maximum natural light of the design and the provision for cyclists, and rewarded other features such as attractive stairwells that encourage staff to walk rather than use lifts. It also requires features such as air quality to be measured and certified – easy to achieve with output from the SBP.

The full scope of the SBP is deliberately undefined. It is designed with flexibility in mind, to accommodate both future demands and future developments: technology is changing fast, but the building is set to be here for a long time.

Hugh Ferguson also talked to Paul Hargreaves and Danny Hall of LRP, and to Ross Harvey and Richard Brailsford of multidiscipline engineers WSP.

Greenhouses cooled by seawater are being used to grow fruit and vegetables in the Horn of Africa © Seawater Greenhouse Ltd

FARMING IN THE DESERT

Growing crops in hot, dry countries can be a challenge. Simple structures that use seawater to keep the growing environment cool are being used to farm fruit and vegetables in the Horn of Africa. Geoff Watts spoke to Charlie Paton, Founder and Director of Seawater Greenhouse, about the challenges of creating a greenhouse that cools instead of heats.

Greenhouses exist to create a warm environment for nurturing plants that would otherwise grow slowly or not at all. So with summer temperatures in excess of 40^{o}C, and warmth hardly in short supply, the arid coastal region of Somaliland in the Horn of Africa is the last place you would expect to see a huge greenhouse.

Some 15 kilometres along the windy coast from the port town of Berbera, you can find two enclosed grow-houses. Unusually, these 'greenhouses' are not designed to provide a warmer environment, but a cooler and more humid one than the hot and dry surrounding air. While the local plant life is little more than small scrubby bushes, these coolhouses support a thriving crop of tomatoes.

Designed and built by a UK company called Seawater Greenhouse Ltd, the structures themselves could hardly be simpler. Charlie Paton, founder and director of the company, worked for many years as a theatre and TV lighting designer, where he developed remote controlled and motorised lighting systems. A combination of holidays in hot and sunny Morocco, and years of thinking professionally about colour and the composition and filtration of light led him to contemplate the paradox of plant growth.

Sunshine comprises visible light and infrared heat. More light leads to more plant growth through more photosynthesis, but too much heat drives water loss through transpiration and, in extremes, reduces growth. It was from these musings that the idea of a new type of growing environment emerged: one that excluded much of the unhelpful infrared in sunshine, while using wind and sun to power a system of evaporative cooling.

PILOT PROJECTS

The first of several pilot projects was launched in the early 1990s with the construction of a coolhouse in Tenerife. Having satisfied themselves that they had proof of principle, Paton's team moved on to the hotter and more arid environments of Abu Dhabi and Oman, the latter in collaboration with Sultan Qaboos University. 'Greenhouses' in both locations experimented with the use of metal support structures. In Abu Dhabi, the company used supports that were similar to the metal frames found in polytunnels. The Oman coolhouse experimented with shade nets.

The first commercially viable and much larger group of coolhouses were installed at Port Augusta in Australia in 2010. An investor commissioned Seawater Greenhouse to set up the project with a view to growing tomatoes. It began as a 2,000 metre squared pilot structure and now, under the ownership of a local company Sundrop Farms, it covers 20 hectares. In addition to the seawater evaporation technology it can also function as a regular greenhouse, which requires energy. This comes in the form of solar power accumulated by an array of 11,000 stands each supporting three mirrors that focus the Sun's rays on to a solar collector mounted at the top of a 100-metre tower. The system has a peak generating capacity of 39 MW. Tomato production is in the region of 15,000 tonnes annually.

Port Augusta is a high-tech project. But far from marking the culmination of Paton's interest in seawater greenhouse technology, this powerful demonstration of its potential led to a radically simpler form, suitable for

The Port Augusta project covers 20 hectares, and produces 15,000 tonnes of tomatoes annually © Mansouraboud68 / Wikimedia Commons

societies that lack the resources of a country like Australia. The Somaililand project, supported in the beginning by a grant from Innovate UK, was built in collaboration with an NGO, the Pastoral and Environmental Network in the Horn of Africa. This coolhouse had to be cheap, rugged and suitable for a smallholding farmer.

SUN AND SEA

Charlie Paton describes the revised structures as "basically a Bedouin tent covering a thousand square metres with a soggy wall of cardboard at either end." Besides an unlimited supply of wind and sunshine, the clue to their other principal requirement lies in the company's name: seawater. The invention relies on a familiar principle – evaporative cooling – but here it is applied in a context where fresh water is scarce and wind and seawater are abundant.

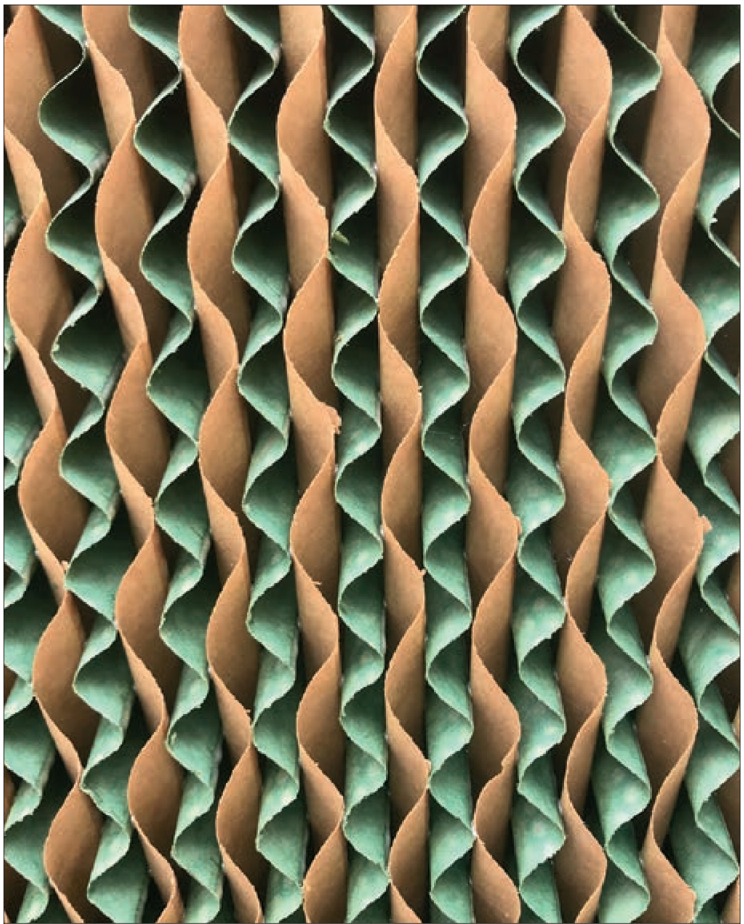
The "soggy walls of cardboard" are actually evaporator panels designed for use in air conditioning systems. Each panel is a pad made up of layers of cardboard that is corrugated with a pitch of 7 millimetres between its trough and peak. The layers are stuck together so that the corrugations in alternate layers run at different angles. This crisscross configuration means that air entering the filter rapidly becomes highly turbulent.

The cardboard panels form permeable walls, one at either end of the structure. Each wall provides a large area for evaporating the seawater that trickles down it. Wind blowing through the panels enters the grow-house both cooled and humidified. Paton's premise is that when cultivating crops in hot, arid regions, humidifying the air has at least the same value as conventional irrigation.

Seawater that remains unevaporated following its downward journey collects in a trough beneath the cooling panels before being pumped back to the top. The whole structure is positioned so that one of its end walls faces the direction of the prevailing wind. If the wind changes direction from onshore to offshore – as, typically, it will at night – the filter at the opposite end of the building will take over cooling duties. Solar power provides the relatively small amount of energy required to pump seawater from the nearby ocean.

MODELLING WINDSPEED

Before construction began, Seawater Greenhouse enlisted the help of the School of Engineering and Applied Science at Aston University, Birmingham to predict the likely temperature and humidity inside the greenhouse. To do this, researchers devised a model that took account of ambient humidity and temperature and its fluctuations, wind speed, intensity of solar radiation, optical and physical properties of the shade nets, rate of airflow through the cooling pads, rate of



The criss-crossed cardboard means that air becomes turbulent, cooling the structures © Seawater Greenhouse Ltd

Beach wells, 200 metres from the beach, use sand to clean and filter water before it is pumped to the grow-house © Seawater Greenhouse Ltd

consequent water evaporation, and much else.

The team's model suggested that a wind speed of as little as 3 m/s would be enough for satisfactory cooling. They found that the evaporative cooling pad would provide a horizontal plume of cold air across the crop cultivation area. This plume would persist for some 10 metres downstream of the cooling pad, and reduce peak season temperatures by up to 10°C. The moisture content of the air in this plume would be increased by 6–9 g/m^3. Beyond 15 metres downstream, the plume would largely dissipate. Although the shade-net by itself would not provide effective cooling, it would help to contain the cold air plume; without it the useful length of the plume would be roughly halved.

Overall the Aston modelling suggested that if the coolhouses were correctly orientated with respect to the prevailing wind, each square metre of the surface of their cooling pads should release 33.4 cubic metres of water vapour to their interior, and generate 2.34 tonnes of salt annually. The greenhouses have, it seems, lived up to these predictions.

Sunlight is necessary for plant growth, but this greenhouse uses no glass or any other material that would create a literal 'greenhouse effect' within its interior. Instead its sides and roof are formed of shade netting designed to reduce the heating effect of the Sun by reflecting much of its infrared component. More than enough visible light gets through to drive the plants' photosynthesis.

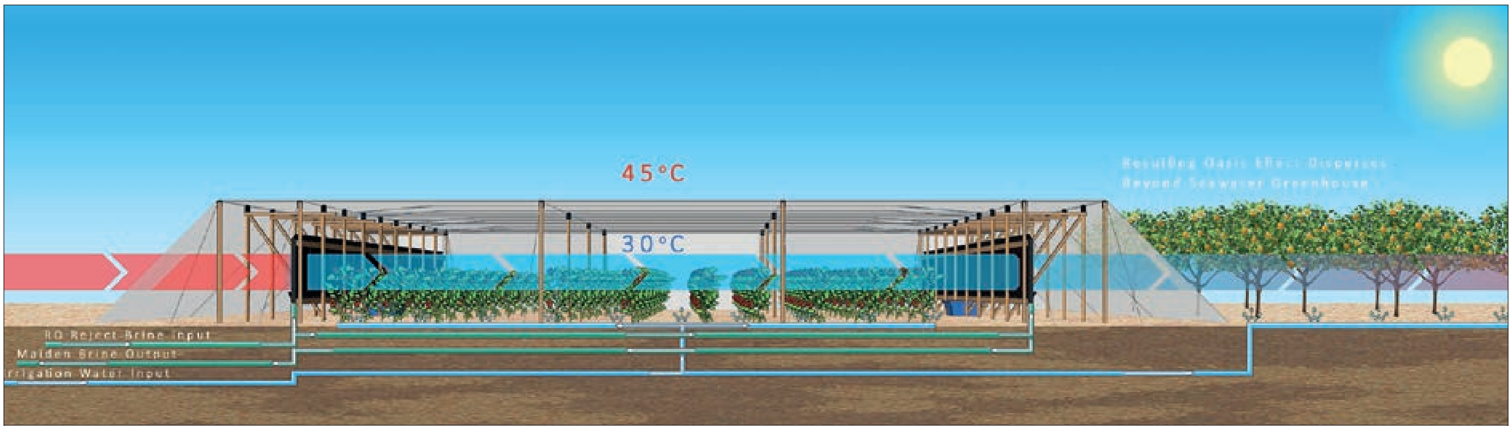
If this all sounds extraordinarily simple, it is – and that's the point. Somaliland is a poor country with few resources. Anything much more elaborate would price itself out of reach.

BENEFITS OF SEAWATER

Only 1.8% of Somaliland is cultivated, and there are few arable crops. Its coast has a year long prevailing wind of around 20 metres per second and an air temperature that reaches 40°C in the summer and seldom falls below 20°C. The two coolhouses on the site measure 30 metres square, made of a roof and side walls of shade netting (with a hole diameter of 3 millimetres and an optical porosity of 50%) supported by wooden poles. The entire width of the coolhouse, at both ends and up to the roof, is filled by the evaporator panels. These stand on low wooden supports beneath which a trough collects the unevaporated salt water that has trickled down the panels. Electric pumps return this water to the tops of the panels.

This recycling means that the seawater becomes concentrated to the point at which salt begins to precipitate out of solution. This tends to begin in the sump tank used to collect the water from the troughs before it is recycled. In practice a fresh batch of seawater is required

The benefits of a seawater greenhouse are not confined to the area within it. Once up and running it produces what Paton calls an oasis effect. Cooler and more humid air leaking from the sides of the coolhouse create a local microclimate above the ground surrounding it. This is sufficient to support the growth of melons, citrus trees and various herbs.



Seawater is pumped into the cardboard walls, evaporating and cooling the air inside the building. The surrounding areas are cooled by the air that leaks from the structures, providing the perfect environment for growing crops like melons and citrus fruit © Seawater Greenhouse Ltd

once a day, and is pumped on to the site direct from the ocean. The concentrated brine it replaces is run off into evaporating trays from which salt crystals can be recovered, dried, bagged and sold.

Calcium dissolved in seawater also tends to precipitate out on the cardboard surfaces of the evaporator panels, forming deposits resembling limescale. This has proved to be beneficial because it turns the cardboard into a firm coral-like structure.

Plant transpiration inside the coolhouse is a fraction of what it would be outside. The small quantity of fresh water required by the crops is supplied by desalination of seawater using reverse osmosis. Power for this, for the pumps, and everything else electrical on the site, is provided by a 10 kW array of solar panels connected to lead-acid batteries. The project is self-sufficient in energy.

Intriguingly, the benefits of a seawater greenhouse are not confined to the area within it. Once up and running it produces what Paton calls an oasis effect. Cooler and more humid air leaking from the sides of the greenhouse create a local microclimate above the ground surrounding it. This is sufficient to support the growth of melons, citrus trees and various herbs.

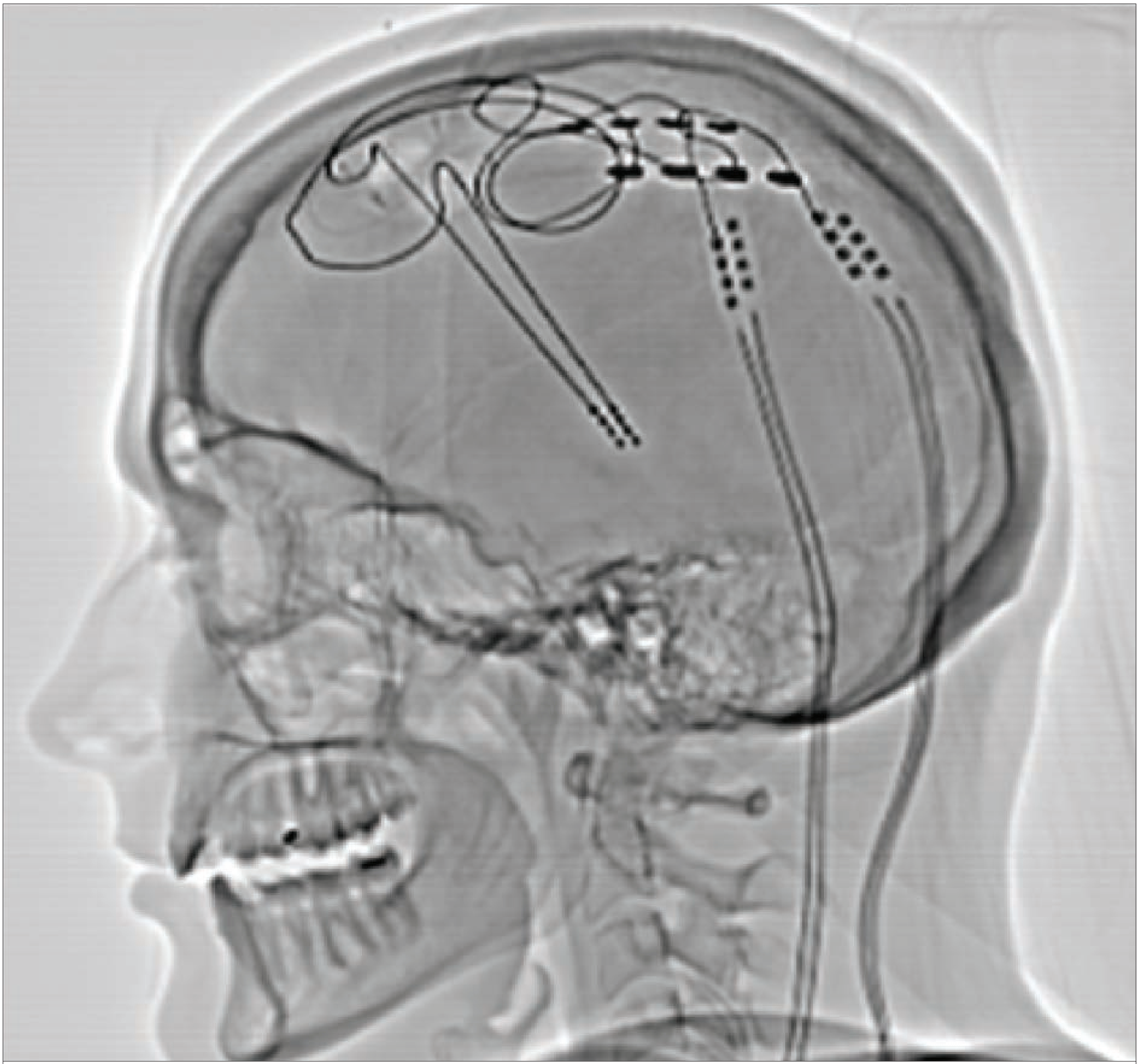
PRODUCTION

The Somaliland greenhouse can produce 300 to 750 tonnes of tomatoes per hectare. This, and the salt (which contributes some 10% to the profit of the enterprise), make it commercially viable – or would do if the region were politically more stable. As it is, the project has to employ three armed guards at a price that absorbs much of the scheme's profit. So how does Paton rate the likelihood of other greenhouses appearing along the region's coast? Right now, he's not optimistic. The technology in this cheap and simple form undoubtedly works, but he sees no imminent sign of the political will that would be required to get more projects like it off the ground.

At a cost of $400 million, 2,000 hectares of seawater greenhouses could give the four million people of Somaliland the daily 400 grams of fruit and vegetables that the World Health Organization estimates to be the minimum requirement for health. What a bargain!

BIOGRAPHY

Charlie Paton is Founder and Director of Seawater Greenhouse. He studied at the Central School of Art and Design in London and began his career as a lighting designer and maker of special effects. His fascination with light and plant growth led to the Seawater Greenhouse concept. Charlie was recognised as a Royal Designer for Industry by the Royal Society of Arts, Manufactures and Commerce.



A post-operative X-ray of electrodes implanted in a patient with severe Tourette syndrome © Professor Gunduz, University of Florida, *Thalamocortical network activity enables chronic tic detection in humans with Tourette syndrome*

BIOELECTRONIC DEVICES

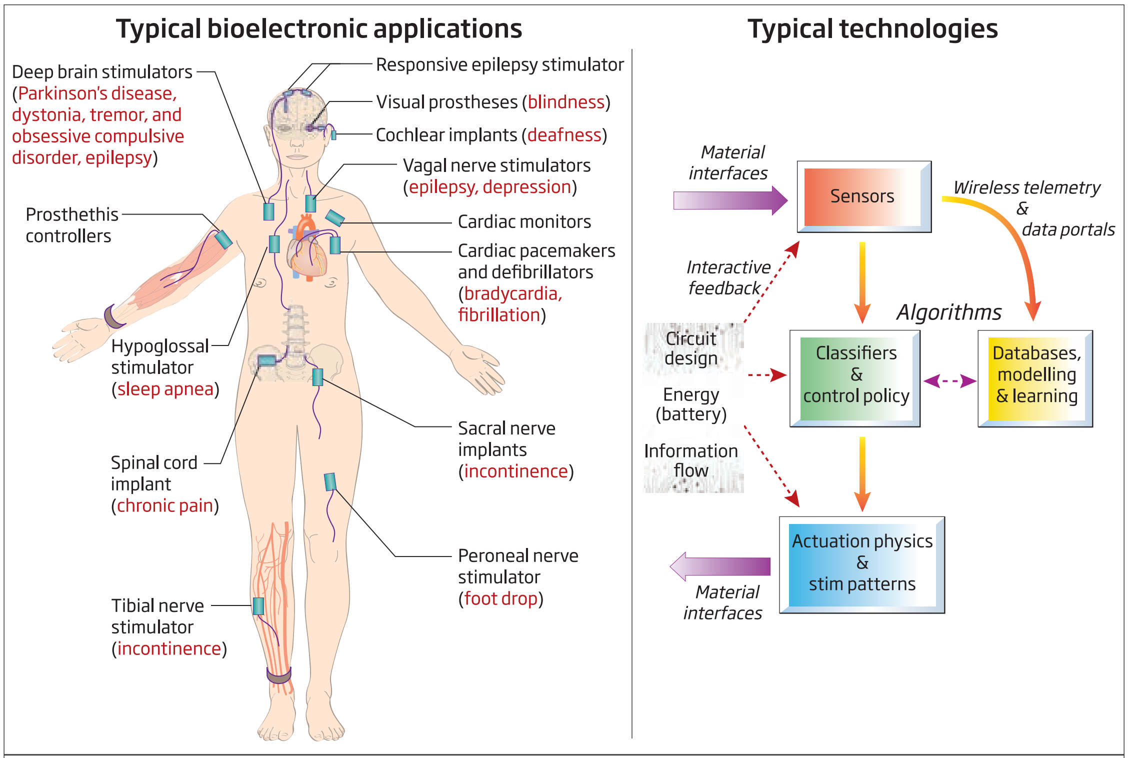
Cochlear implants and heart pacemakers have drastically improved the lives of many people with long-term health conditions. Professor Tim Denison looks at implantable medical devices and the engineering behind them as digital technologies and miniaturisation promise to deliver new therapies and help us to understand how the nervous system works.

Neurological disorders and related diseases of the nervous system create an estimated annual economic burden of over £100 billion in the UK, a cost that does not capture the personal impact of disease. When treating these disorders, doctors generally turn to pharmaceuticals but for some illnesses, bioelectronic systems are an effective alternative. They interact directly with the body's own nervous system to monitor physiological signals and to control electrical activity to alleviate symptoms. Early examples of this approach have been cochlear implants to treat hearing loss and cardiac pacemakers to maintain a healthy heart rhythm. Engineers and clinicians are developing other bioelectronic applications including brain stimulators, cardiac and physiology monitors and spinal cord networks.

The most familiar device among the first generation of bioelectronic systems has been the cardiac pacemaker. In the early 1950s, the first pacemakers were relatively large portable systems that stimulated hearts after surgery. Around the same time in Minnesota, US, Dr Walt Lillehei performed reconstructive surgery on children with congenital heart defects. He used thermionic vacuum tubes to create a system that delivered electrical impulses to a wire electrode inserted into the right ventricle. This system, the size of a suitcase, relied on mains electricity that would fail in power cuts. In a bid to overcome such obstacles, Lillehei turned to his colleague, Earl Bakken, an electronics engineer, for help to develop a more reliable solution. Bakken adapted a two-transistor metronome circuit from a hobbyist magazine to create a battery-powered portable cardiac pacemaker that was easy to use. This first semiconductor device paved the way for other implanted electronic systems. A few years later, William Chardack, an American medical doctor, and Wilson Greatbatch, an engineer, further miniaturised the pacemaker circuit and encased it in epoxy, making the first fully implantable pacemaker a practical reality.

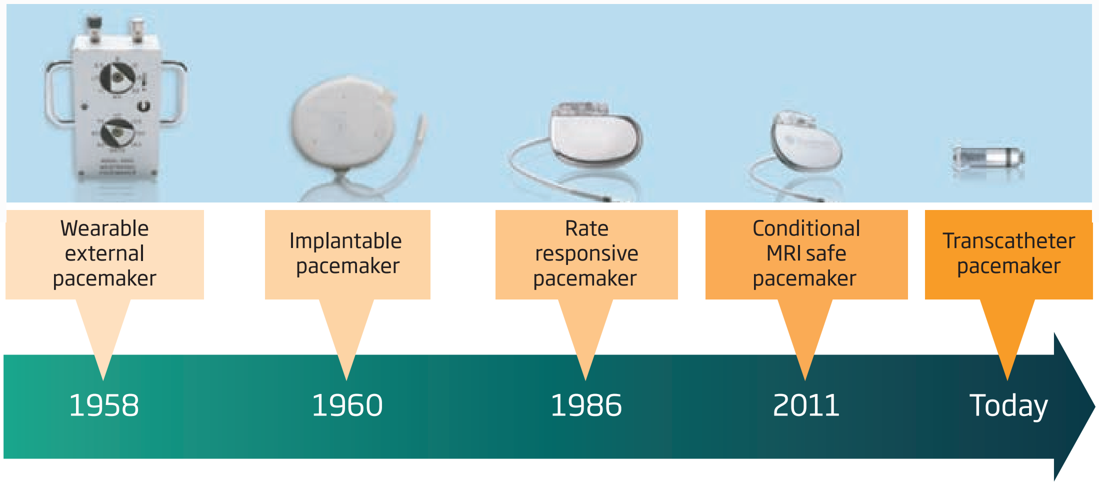
Over the past 50 years, the cardiac pacemaker has evolved to include multiple sensors for monitoring the patient's heart rhythm, activity and breathing. The addition of embedded microprocessors made it possible to optimise pacing with algorithms tailored for each patient. The addition of wireless telemetry has further enabled clinicians to monitor patient symptoms and address issues remotely.

Engineers have overcome the original challenges, such as preventing damage by encapsulating the electronics, and designing an insulated lead wire that could withstand continuous bending – the heart contracts more than 30 million times a year. They have



Bioelectronic systems (left) raise important issues that engineers must consider when creating devices that interface with the nervous system (right) © Jane Fallows also reduced the size of the implanted device from a cricket ball to a small AA battery. Doctors can now place a pacemaker into the body it through a vein, in the same way that they insert stents into arteries.

Cochlear prostheses followed a similar trajectory to cardiac pacemakers. Some types of deafness arise when the small transducers, hair cells, in the inner ear can no longer convert acoustic energy into electrical impulses. Sound produces mechanical motion that usually creates currents in the cells that relay information to the brain, but damaged cells block the transmission.



The evolution of cardiac pacemakers

The purpose of the cochlear implant is to take over from hair cells as the source of electronic impulses – see *Cochlear implants*.

IMPLANT ADVANCES

Bioengineers have begun to adapt the same principles that cochlear implants use to bypass other damaged sensors in the body. For example, a retinal prosthesis can be applied to damaged photoreceptors in the eye. The prosthesis converts light detected over a region of the retina into currents that excite the eye's remaining cells. Doctors now implant these systems in blind patients for diseases such as retinitis pigmentosa. The prostheses electrically stimulate surviving retinal neutrons, which the brain can then interpret as vision. The algorithms used for perfecting stimulation of the retina are also evolving as we learn more about sensory processing in the eye.

The success of cardiac pacemakers, cochlear, and now retinal prostheses has helped generate new implantable systems for treating disease that interact with many circuits in the nervous system. For example, 'brain pacemakers' routinely treat the symptoms of movement disorders such as Parkinson's disease, essential tremor and dystonia. With a brain pacemaker, a surgeon routes an electrode to a specific area of the brain related to the disease. Pulses of electricity excite new rhythms that help to suppress its symptoms.

Other devices are used to treat epilepsy. Embedded amplifiers and implanted sensing electrodes can detect seizures and other bioelectrical waveforms. Using algorithms to interpret the brain's signals, these devices then stimulate the brain to control the symptoms. These responsive implants for epilepsy were designed using similar principles to a cardiac defibrillator: to sense an emergent state, such as a cardiac arrhythmia or seizure, and then apply a burst of stimulation to try and stop it. Similar adaptive systems are now being explored to improve the treatment for Parkinson's disease, Tourette syndrome and obsessive compulsive disorder, where different stimulation settings might be required to accommodate variations in medication or the patient's environment.

Doctors can also to treat chronic pain by placing implants along the spinal cord, with stimulation electrodes positioned over the nerve area that is associated with the area of pain, taking advantage of the nervous system's mapping in a way similar to a cochlear implant. Electrical stimulation in these areas modulates the activity in the nervous system to alleviate the perception of pain.

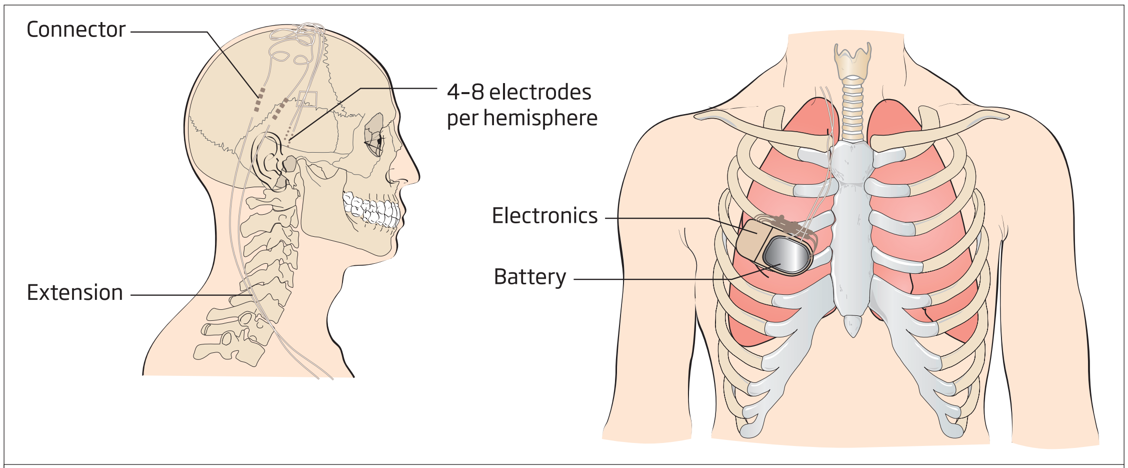
COCHLEAR IMPLANTS

Cochlear implants bypass damaged hair cells in the ear and convert sound from a microphone into electrical pulses in the inner ear.

An electrode winds through the inner ear to localise the stimulation currents within the cochlea. Unlike the cardiac pacemaker, which has one lead for each heart chamber and is usually restricted to the right atrium and ventricle, cochlear implants can have up to 22 electrodes spaced along the cochlea. This arrangement gives greater precision for recreating the recipient's experience of sound.

The prosthetic's electronic circuits estimate the frequency of the auditory signal, and convert it to the amplitude of stimulation at specific tuned electrodes along the cochlea.

Over recent decades, the algorithms and software for implementing this processing have evolved to replicate better hearing. Encoding certain auditory signals such as music remains a challenge. Despite these limitations, the cochlear implant is one of the most successful prosthesis, with hundreds of thousands of people benefitting from it.



A brain pacemaker system – The schematic on the right, derived from an X-ray image, shows the implanted battery and electronic circuit placed in the chest. On the left, electrodes are routed through the neck and a hole in the skull, where a neurosurgeon has placed them into a specific location in the brain's circuitry © Jane Fallows

Descending further down the spinal cord to the area of the sacrum, similar methods can treat urinary and faecal incontinence by stimulating nerves that can influence the anal or bladder sphincter muscles. Stimulation of the sacral nerve builds on a long history of technologies for managing the bladder. These devices intercept and override signals in the reflex pathways of the bladder to help with maintaining continence. Researchers are working on further refining these techniques for the treatment of spinal cord injuries. While there is a simple explanation for how these therapies work, the true 'mechanism of action' often remains a mystery. Neuroscientists are working with engineers to study the basic science and to improve bioelectronic systems.

DESIGN CONSIDERATIONS

To design a successful medical implant, engineers must solve multiple challenges, including creating suitable materials, battery technologies and electronics, and information security. The materials interface must not cause inflammation or harm the surrounding tissue. In addition, the body's harsh biological environment – warm, salty and corrosive – must not damage implants that have to last more than a decade.

The implant's energy requirements, hundreds of microwatts to milliwatts, needs new battery technology and management. Battery miniaturisation has already delivered improvements on this front. In terms of sensors and computation, the trends in microelectronics have also transferred to implantable systems. Most designs now use at least one microprocessor to manage the system, monitor and report on self-diagnostics such as electrode integrity, and in some cases, to adjust stimulation to optimise the treatment based on sensor measurements.

As systems become 'smarter', it is increasingly important to consider data privacy and device security. Managing these risks, a fundamental part of medical device design, depends on good design practices such as systematic analysis of failure modes and risk mitigations. The design of a medical system truly requires a multidisciplinary, systems-based approach.

In spite of their capability, implantable bioelectronic systems have several attributes that limit their adoption. One key issue is that implants require a skilled neurosurgeon to place the devices in the body. Engineers are constantly seeking ways to minimise invasiveness, while maintaining appropriate stimulation of the nervous system.

For example, healthcare professionals and engineers can apply more advanced non-invasive transcranial techniques that rely on external stimulation of the brain rather than implants to deliver therapy more deeply – either in the brain or to synchronise different regions of the brain. While non-invasive methods have the advantage of not requiring surgery, they are generally less specific at treating disease compared to an implant. In addition, patients can be put off by the need to wear a bulky appendage.

FUTURE APPLICATIONS

Technology is evolving on several fronts, from reducing invasiveness to using sensors and digital technology to providing better therapies. There is also a focus on microfabrication to create miniature versions of systems to minimise the invasiveness of implantable systems.

For example, researchers are exploring the possibility of using a stent to insert brain implants. The device is routed through the vascular system to a targeted location in the head. Bioelectronic systems are having an impact, but engineers need to continue working with clinicians and neuroscientists to resolve technological and scientific issues so that these new techniques can become standard care.

Concepts from the Internet of Things are also influencing thinking on medical implants. Digital technologies can address various diseases using software modifications, as well as fine-tuning to a patient's needs. In future, sensors and algorithms could lead to systems that respond to physiological fluctuations within the body, allowing the possibility of building restorative prosthetics that serve more like a surrogate nervous system than a simple implant.

Gaps in our understanding of how the nervous system works still limit the design of bioelectronic systems. To this end, bioelectronic platforms also open a window into the nervous system and how it works. As well as providing therapeutic capability, clinician-researchers can put scientific instruments inside devices to gather data on how the nervous system functions, goes awry due to disease or responds to drugs and stimulation. Engineers are working with human volunteers to meet clinical needs, including balance problems caused by Parkinson's disease, predicting and preventing seizures in epilepsy, and emotional and sensory processing of chronic pain and depression. These experiments also help researchers to understand how to restore neurological function, and prototype future interventions.

Bioelectronic systems have changed how we treat neurological conditions. Engineers need to continue to work with clinicians and neuroscientists to resolve technological and scientific issues so that these systems can become the standard of care. As with most engineered systems, medical implants have conflicting constraints: the role of the engineer is to design systems that balance these trade-offs and provide different options for the clinician.

In the last half century, Biomedical engineering has made great progress in the treatment of neurological disorders. As electronics and computing develop, disciplines such as artificial intelligence, advanced materials processing and manufacturing, and battery technology will be integrated into new systems that will help to make further significant breakthroughs in the treatment of neurological diseases.

PICOSTIM

Several UK companies are pioneering the next generation of bioelectronic medicines. Bioinduction Ltd is developing the Picostim brain stimulator, which works like a pacemaker for the brain. It is being investigated as a way to treat neurodegenerative diseases, such as stroke, hypertension and Parkinson's. Picostim miniaturises the electronics, battery and packaging for the stimulator so that it can be placed on the head, right beneath the skin, similar to the cochlear implant. The small device eliminates the need to tunnel electrodes through the neck region and chest, and means that placing a large device in the chest cavity is no longer necessary (see brain pacemaker diagram on the left). It is one third of the size of existing brain stimulation systems, and can be implanted in one surgery, rather than the two that older devices require.

Picostim uses a battery that can be recharged through a small head coil, which should allow the system to operate for more than a decade. Rechargeable systems help avoid follow-on surgery, and save money by avoiding replacing devices. In addition to providing stimulation to the brain, the Picostim system has embedded sensors and digital signal processing, which will allow clinical researchers to prototype new closed-loop therapies in the future. Galvani, a GSK partnership with Verily, is looking to apply bioelectronics for precise control of the nervous system. Galvani has ongoing efforts to see how electronics might provide more specific control of organ systems, and has a large network of academics exploring the options.

Bioinduction Ltd's Picostim Brain Stimulator system is small enough to be placed directly on the skull, like a cochlear implant © Bioinduction

BIOGRAPHY

Tim Denison is a Royal Academy of Engineering Chair in Emerging Technologies at the University of Oxford, where he explores the fundamentals of closed-loop systems. Prior to this, Tim was Technical Fellow for the Restorative Therapies Group at Medtronic PLC, where he helped oversee the design of next-generation technologies for the treatment of neurological disease. He has a PhD from MIT in electrical engineering, and an MBA from the University of Chicago.

COMPOSITES TAKE OFF

When the Airbus A220 took to the air, it flew with the first certified commercial aircraft wing made using resin transfer infusion. The composite, carbon fibre wing is 10% lighter than a metal one, which reduces its environmental impact by consuming less fuel while flying and requiring less energy for its manufacture. These achievements won Bombardier the 50th anniversary MacRobert Award for engineering innovation. Michael Kenward OBE talked to Professor Ric Parker CBE FREng, a special advisor on technology and technology transfer and MacRobert Award judge.

An advanced composite wing being lifted from a jig in final assembly © Bombardier

The autoclave area in the Wing Manufacturing and Assembly Facility at Bombardier Belfast where the wings are cured © Bombardier

Truly revolutionary advanced innovations in materials technology do not come along every day. Bombardier's composite aircraft wing is a rare example of a leap forward in materials and manufacturing engineering that has changed how this industry works. It underpins the success of the Airbus A220, which made its maiden flight in September 2013 and entered service in July 2016 as the Bombardier C Series. The plane was made to fit into the 100- to 150-seat market, which has increased in the last decade and Airbus has picked up a significant proportion of the new sales in this area. This is due in no small measure to its composite wing, with attendant reduction in assembly line costs and improved lifecycle maintenance savings.

The MacRobert Award, a rare accolade for materials and manufacturing innovation, was awarded to Bombardier for the patented resin transfer infusion (RTI) process used to make the wings. The patent protection covers the RTI process and the tooling needed to make it happen. Before this innovation, only small-scale pieces could be made by resin infusion. The Bombardier wings represent a huge jump in application as the largest and most complex structure designed using this technology.

LONG TRACK RECORD

Bombardier's Belfast operation had been researching and developing composites since the 1970s. It was involved in the Next Generation Composite Wing project, a government-backed three-year programme, launched in 2008, which brought together leading aerospace companies in a £103 million research and development initiative that helped to put the UK at the forefront of the use of composites in aircraft.

Composites had already been making steady inroads into aerospace. Most composites that go into today's aircraft programmes start with a material that arrives as a tape pre-impregnated with resin (pre-preg). This relies on curing the material under high temperature and pressure, usually in an autoclave, to bind the fibres together to create a hard and durable structure. The pre-preg material used by other large airplane manufacturers has to be stored in a deep freeze and material is wasted if left at room temperature for too long.

Bombardier decided to use 'dry' fabrics placed in moulds to create the structure. Liquid resin is then injected into the structure before heat and pressure are used to cure the composite in the autoclave. It soon became clear that this RTI process created new possibilities. It meant that large complex structures could be manufactured as single pieces, which in turn reduced the need to make many different parts that have to be assembled with mechanical fasteners or glued together after production. This approach offered significant material savings and reduced manufacturing times.

PRODUCT TESTING

Bombardier decided to create a composite wing as part of a development project for the Bombardier C Series of narrow-body, twin-engine, medium-range jet airliners. The CS100, (now known as the Airbus A220-100), required a 35-metre wing for its planes that would carry between 100 to 150 passengers.

A220-100 aircraft in flight © Airbus

Introducing a new material into something as safety-critical as aerospace needs extensive research to prove that the design, manufacturing and assembly can deliver safe and reliable components that meet all the stringent certification requirements for any new aircraft. This process involved a research and development programme that entailed thousands of individual material and component tests.

The development programme also included producing a full-scale, three-quarter span, pre-production wing. This was tested to ultimate load, replicating 150% of the most severe forces that the wing is likely to experience in service. The data collected from all the tests then fed into optimising the design of the production wings.

One of the major challenges in wing design is coping with lightning strikes. A carbon fibre structure is less conductive than aluminium, so engineers needed to address a number of challenges to receive certification, not least because it was a brand-new design. Punctures at fuel-tank boundaries and arcing from fasteners, interfaces and system installations can be prevented by designing appropriate electrical pathways and ensuring there are no gaps that create sparks. To do this, Bombardier has developed and patented high-resistance components and support brackets, which were validated through 3D computational electromagnetic modelling.

Engineering new materials, and ways to work with them, is just a part of the innovation process. Engineers also have to devise new processes and approaches to manufacturing. Most commercial aircraft wings are made of aluminium alloy. They have a large number of individual parts manufactured from pieces of plate, extrusion, forgings or sheet material. These metal parts are machined and formed to the required shape.

ENVIRONMENTAL IMPROVEMENTS

The new RTI material process has led to a significant improvement in the environmental performance of aircraft of its size and range. "The composite wing enables the lightest, and most fuel-efficient aircraft in its class in the Airbus A220, contributing significantly to the reduction of CO_2 from air transport," says Parker. "While aircraft contribute only 2% of man-made CO_2 to global warming today, if we do nothing, they will soon be a major contributor." The lighter wing not only results in reduced fuel burn but in a reduction in NO_x emissions because of the state-of-the-art aerodynamics.

The dry fibre used by the Belfast team can be stored at normal room temperature condition, reducing energy and wastage, unlike pre-preg material, which requires refrigeration to maintain the resin texture.

Offcuts of the pre-preg material cannot be reused and usually end up in an incinerator or as landfill. However, the dry fibre offcuts can be recycled and reused for other chopped or short fibre composite products.

It isn't just the composite wing, however, that contributes to the Belfast facility's 'green' credentials. The new wing factory includes sustainable initiatives that include recycling stations to segregate waste for reuse or recycling. The factory also employs specialised equipment to optimise energy efficiency and reduce environmental impact.

In another first, the largest rooftop solar installation in Ireland, and one of the biggest in the UK, helps to reduce the company's reliance on fossil fuel and its energy costs. Installed in 2015, the roof of the wing manufacturing and assembly facility has 14,000 solar photovoltaic panels, generating annually approximately 2,800 megawatt hours of renewable energy for Bombardier.

A one piece A220 wing skin produced by the RTI process © Bombardier

Bombardier aircraft fitters work on kitting out the wing in final assembly before despatch © Bombardier

These individual parts are then put together with rivets and bolts to create the wings.

Complex fabrication and assembly processes used for turning sheets of metal into wings are no help when you want to take deliveries of fabric at one end of the production line and deliver whole wings at the other end. Bombardier set up a production and assembly line in a new 56,000 square metre facility in Belfast which was opened in 2010. This £520 million investment in the aircraft wing programme is the largest-ever, single inward investment in Northern Ireland, and one of the largest in the UK.

Under one roof it receives raw carbon-fibre material, and then handles cutting and lay-up. There then follows the RTI production system, non-destructive testing, wing assembly and testing, through to delivery of completed wings.

INCREASING APPLICATIONS

The impact of Bombardier's expertise in advanced composite components goes beyond developing and supplying wings for the Airbus A220. The company's portfolio of composites runs to around 30 components, including nacelles (a housing that holds engines, fuel or equipment), landing gear doors, and flight control surfaces, such as flaps, ailerons, elevators and rudders. RTI composites are also used in the horizontal stabiliser for the Bombardier Global 7500 business jet.

In addition, the Belfast operation uses the process to make fan-cowl doors for the supplemental type certificate repair market – issued when Federal Aviation Administration approval has been given to modify an aeronautical product from its original design. This involves replacing the honeycomb interior of fan-cowls with a monolithic structure, resulting in a one piece, lighter and more durable component.

Overall, the new wings have been a great success for Bombardier, their sales helping deliver the first company profit for five years in 2018. The company delivered more than 25 wing sets in 2018, and this is expected to increase significantly in 2019.

The Belfast facility also taps into around 200 suppliers across the UK that provide materials, systems hardware, parts, equipment and services for the wing programme, with many more throughout the whole supply chain. Bombardier's own workforce on this wing programme will include 1,000 people at peak production and thousands more in its wider supply chain.

Bombardier's trailblazing in the development of composites for aerospace applications has paid off both financially and with the engineering peer recognition provided by this latest award. Michael Ryan CBE FREng, Aerostructures Chief Operating Officer at Bombardier Aviation, said: "We've been developing our advanced composite expertise in Belfast for half a century now and it's an immense honour to receive the gold medal in the MacRobert Award's 50th year."

HIVES OF ACTIVITY

Bots whizz around the two grids at Erith, each the size of three football pitches and holding nearly up to 3,500 bots © Ocado

Ocado's new automated warehouse in Erith is one of the most sophisticated in the world, with thousands of robots collaborating to pick and pack customer grocery orders. Neil Cummings spoke to Paul Clarke CBE, Ocado's Chief Technology Officer, to find out more about the innovations that make the online supermarket work.

Grocery shopping has always been an unwieldy process. Items are delivered by lorry on pallets to a supermarket warehouse, where they're broken down onto smaller cages and then stacked onto shelves. Customers pick these items and place them into a trolley or basket before depositing them on checkout conveyors, packing them into bags, transporting them home, and putting them away.

The development of online grocery shopping helped to eliminate several steps from this inefficient process, but the remaining stages still relied on human labour. When Ocado debuted in 2000 as a specialist online grocery retailer, its founders recognised the efficiency of automation. The following year, it unveiled a Customer Fulfilment Centre (CFC) in Hatfield, which had automated as many of the picking and packing stages as possible.

While Hatfield remains one of the world's biggest and most futuristic online grocery warehouses, it's recently been eclipsed by a new facility in Erith. Measuring over 52,000 square metres and taking over three years to build, this CFC demonstrates how much of the grocery supply chain can be streamlined through investment in everything from swarm robotics technology to pioneering software modelling.

At any one time, there are around 8,000 plastic crates on the move across 32 kilometres of conveyor. Over 150,000 orders per week are dispatched from this warehouse © Ocado

SCALABLE SHOPPING SOLUTIONS

As Ocado's Chief Technology Officer, Paul Clarke has played a key role in developing the world's biggest online-only supermarket brand. He points out various inefficiencies in the traditional online grocery model: "With an average item price of £2, there is about 60p of margin to pay for the decant, storage, picking, packing and delivery to customers' kitchen tables in one-hour slots. It was therefore a cornerstone of our founding vision that the only way to do online grocery delivery scalably, sustainably and profitably would be through the application of a huge amount of technology and automation."

This was unexplored territory, because there was no template for automated warehousing. Ocado had to develop almost all of its software and hardware in-house. This is evidenced by the engineering inside the initial Hatfield warehouse, which at over 16 years old is still one of the largest and most advanced online grocery warehouses in the world. At any one time, there are around 8,000 plastic crates moving across 32 kilometres of conveyors, with cranes, shuttles and machines moving around under software control.

This type of warehouse design makes sense in the UK, which has one of the most evolved online grocery markets in the world. Per head of population, only South Koreans buy more groceries over the internet than we do. Ocado knew that in other emerging markets, it needed a solution that was more modular and scalable, while still efficient. This drove Ocado to evolve the swarm robotics technology that powers its Erith CFC.

ROBOTIC CHESS

In Ocado's second-generation CFC at Erith, thousands of robots help to source and assemble customer orders. They inhabit one of two huge chessboards, referred to as hives – one for ambient products, and another for chilled goods. With two perpendicular wheels at each corner, the cubic robots move across rows or columns of rails surrounding square bins, each of which contains a specific item. Bins are stacked up to 21 deep, creating a truly three-dimensional storage model and the densest storage possible. Simulations worked out that 21 was the optimal number of bins for a stack, based on factors such as fulfilment needs, space available and strength of tote material. Robots are programmed to stop above a particular stack and lower a grabbing mechanism to pick up a bin. They will then either drop it off on another stack to access the bin below it, or bring it to a pick station where humans place the items in a customer's order basket.

Each hive is the size of three football pitches, populated by over 1,700 identical robots that are collectively capable of picking a typical 50-item customer order in around five minutes. The real ingenuity of this system is that every robot is working collaboratively in real time, as Paul explains: "There is no way we could achieve the required throughput if the robots were autonomous, moving around the grid dodging one another. Instead, the swarms of robots are orchestrated by a machine learning-based system that is playing chess many moves ahead. It knows which bins need to be where, and which robots it needs to schedule to complete every order in a perfect pick sequence."

On a busy day, the total distance covered by Erith's chilled and ambient hive robots could reach 179,778,363 metres – equivalent to travelling around the Earth four and a half times. This all takes place in a relatively confined environment, with robots passing one another at 8^{ms-1} with less than 10 millimetres clearance. To achieve this level of precision requires the control system to talk to each robot 10 times a second. To do this, Ocado developed a proprietary communication system, with LTE mobile technology operating across the unlicensed spectrum. The system involves slicing the time/frequency spectrum up into cells, and each robot gets one cell that only it is able to use. If a robot needs to communicate more, it can be allocated extra cells.

Bots generate about 5,000 data points, 1,000 times a second – that's one gigabyte of data per bot per day © Ocado

WORKING IN HARMONY

Each robot is granted clearance to move to a particular location within the hive. As it moves away from a square, it raises a notification that the square is clear for another robot to enter. As well as optimising movement, this ensures robots don't collide, even if one unexpectedly stops working due to a mechanical breakdown. This rarely happens, since the robots are constantly providing feedback data. If a machine needs repairing or servicing, it can be temporarily removed from the swarm and repaired off-grid while other robots seamlessly take up the slack.

The control system managing this synchronised three-dimensional ballet not only optimises the routing of the robots on top of the hive in real time, but also optimises the three-dimensional storage of the bins underneath the robots. It does this while looking forward in time to ensure that when bins are moved, they're in optimal positions based on when they're likely to be needed next.

The bins aren't grouped according to their contents, so you won't find 10 brands of kitchen roll in 10 consecutive baskets. Instead, the control system optimises the layout of the hive, based on when each bin is programmed to be needed next. This is calculated using a combination of variable factors, including the customer orders that have been placed, the orders that are expected to be placed, and external factors that alter the demand for each product, which might include weather, promotions or celebrity chef recipes.

DIGITAL TWIN

Ocado has also developed a digital twin of the Erith hive. The phrase 'digital twin' describes a virtual equivalent of a real-world product or service. As an example, modelling software creates virtual copies of objects already in existence, so they can be stress-tested and used to generate diagnostics in a safe environment. Data from Erith is fed back to its digital twin, as Paul explains: "We use these digital twins to test new algorithms, to examine production software before deployment. Then we are able to playback and visualise production data for analysis and troubleshooting."

WASTE NOT, WANT NOT

The resulting centralised fulfilment model offers many efficiency and productivity advantages over alternative solutions such as store picks. This was the traditional method of online grocery fulfilment, with staff manually navigating around customer-free stores designed to suit the needs of packing personnel rather than shoppers. Erith also stocks a larger product range than any conventional UK supermarket, with around 54,000 products across three distinct temperature regimes. Because a computer is overseeing everything from orders in progress to impending goods deliveries, customers are spared the frustration of ordering items that are out of stock by the time their order is fulfilled.

There are other benefits to a highly automated warehouse system for groceries. Algorithm-controlled picking and packing slashes waste compared to normal supermarkets. Where a conventional supermarket might ultimately throw away three items out of every 100, the ratio at Erith is one in 6,000. Substitution levels are also among the lowest in the industry thanks to computerised stock control and just-in-time ordering processes. In 2018, 98.8% of orders were delivered exactly as ordered.

GETTING A GRIP ON THINGS

One of the biggest challenges facing robots in a facility like Erith is the sheer variety of product sizes, shapes, weights and

Ocado's robotic picking system uses a suction cup attached to an articulated arm. This is guided by a computerised 3D vision system that calculates grasping points on an object regardless of its shape and deformability
© Ocado

materials. While pre-packaged goods may offer predictable sizes and weights, a fragile foil-wrapped Easter egg will require very different handling from a bottle of wine or a bag of frozen vegetables. The robots also have to contend with infinite variations in fresh produce – no two fruits or vegetables will be exactly alike. Until now, this has required humans to complete the final stages of order packing. That represents another obstacle on the road to full automation, which Ocado has been attempting to overcome for years.

"Specific items need different grippers and varying strategies for grasping them," Paul admits. From babyhood, humans learn strategies for picking things up. "For example, if you're going to insert a bottle into a wine rack, you instinctively know to hold it by the neck so your hand won't be in the way, and you anticipate the forces that will be required to carry the bottle. If you want to pick a piece of paper off a table, you'd probably slide it to the edge, rather than crumple it."

"These strategies are instinctual to humans, but robots have to either be taught them or be allowed to learn them. Initially, we will start allowing robots to pick items using a simple suction gripper, while we continue to work on more advanced grippers that mimic the capabilities of human hands." These artificial limbs use the principle of environmental constraint exploitation to create an orchestrated interaction between the robot, the object and the environment. Modelled on the way humans use their hands, a 3D camera identifies opportunities for environmental manipulation. A robotic hand then sequentially closes its 'fingers' around the object, adapting to the shape it needs to pick the item up without applying too much force. Once this has been refined to the point where items aren't dropped or damaged, one of the few remaining human elements of the Erith warehouse could be eliminated.

A SIGN OF THINGS TO COME?

As Ocado improves its algorithms and optimises the efficiency of its robots through simulation learning, each new fulfilment centre operates more effectively than its predecessors. Following a three-year construction and fit-out period, it took Erith's army of robots just 14 weeks to achieve the same level of throughput as the previous CFC had achieved over its first 15 months of operation. Erith was the world's largest automated warehouse for online grocery retail when it opened last year. However, the technology underpinning it is likely to populate far larger warehouses overseas as foreign consumers embrace the relative simplicity of ordering groceries online. Indeed, there may come a time when customers might not have to order groceries at all. AI and machine learning could ensure items are delivered to individual households as and when they're needed, without any customer involvement at all.

BOTS AND DASHES – ERITH'S DATA LAKES

Each robot at Erith generates a significant amount of data, which requires processing to be useful in terms of future planning or refining the existing system. The computational power required to process this constantly evolving data stream is enormous. The bots generate about 5,000 data points, a thousand times per second. That's one gigabyte of data per bot per day, or a total of four terabytes per swarm per day.

The data is processed in various ways; for instance, half a petabyte of raw batch and streaming data is supplied to Google's BigQuery analytics platform for customised analysis. The bot controller software is capable of completing three million routing calculations per second. Along with operational and sensor data from the bots, this is streamed to a data lake in the cloud. A machine learning system conducts analytics for monitoring, oversight and predictive maintenance.

Ocado is in the process of rolling out new software at Erith, which will see around two billion messages a day being sent and received. The bot controller software has been christened Dash, and is capable of completing three million routing calculations per second. However, this isn't as memory-intensive as might be expected, only requiring around 50 GB of space to complete its calculations.

BIOGRAPHY

Paul Clarke CBE is Chief Technology Officer at Ocado. He joined the company in 2006, initially working on warehouse control systems before joining the team designing Ocado's next highly automated fulfilment centre. Since taking on the role of CTO in early 2012, Paul has focused on growing Ocado Technology to over 1,300 engineers and is now focused on the research that will future-proof the Ocado business.

SILVER MEDALLISTS

The Royal Academy of Engineering Silver Medal was established in 1994 to recognise an outstanding personal contribution to British engineering that has resulted in successful market exploitation.

DR DANIEL ELFORD, CHIEF TECHNOLOGY OFFICER, SONOBEX

Dr Daniel Elford is the Co-Founder and Chief Technology Officer of Sonobex Ltd, a company that is developing acoustic metamaterials to solve noise pollution problems. The harmful effects of noise have been linked to up to 50,000 fatal heart attacks every year and 200,000 cases of cardiovascular disease in the EU.

For decades, the way to counter noise in the built environment was to use a variety of barriers, silencers and absorbing materials, such as mass for an acoustic barrier or absorption for a ceiling plate to reduce the echo in a room. Sonobex came up with something entirely new: metamaterials. Metamaterials do not use physical properties to control noise, but instead use the shape of objects.

The technology uses artificially engineered structures that create acoustic effects not found in nature. They can control low frequency sound and can be tuned to control, direct and manipulate noise.

The company has developed the first commercially available, acoustic metamaterial-based technologies that are revolutionising industrial noise control and enabling significant low-frequency noise reduction. The company designs and manufactures a range of modular engineered systems incorporating NoiseTrap® acoustic-metamaterial based panels. These acoustic panels are being used in several industrial projects and other products are close to release.

JENNIFER GRIFFITHS MBE, FOUNDER AND CEO, SNAP TECH

Jennifer Griffiths' innovation, Snap Tech, works with retailers, social media and publishers to help customers quickly find and compare fashion items online. Retailers can use Snap Tech's 'Snap Similar' button to show customers clothes that match the colour or cut of others they have browsed. Publishers can make use of 'Snap the Look' to tell readers where to find a whole outfit from a single photo, along with where to find similar outfits.

Jennifer Griffiths began writing the algorithms that power Snap Tech while she was studying for her master's in computer science at the University of Bristol. She spent three years developing the idea into a business, which is the world's first cross-platform visual search site for fashion and launched in 2012. After raising initial funding herself, she marketed the technology to business-to-business clients, focusing on retailers and publishers such as *Marie Claire*. She joined the Academy's Enterprise Hub SME Leader programme in 2017.

Snap Tech's technology combines hand-crafted mathematical rulesets – a problem-solving technique that quickly narrows a range of possible results to an approximate solution – with the latest machine-learning technology to deliver visually-matched results from an original query image. It takes user-generated images from social platforms, for example, and delivers results that can then be filtered. The technology can be used on the web, via mobile, or in-store.

PROFESSOR PAUL NEWMAN FRENG, UNIVERSITY OF OXFORD, FOUNDER AND CTO, OXBOTICA

Professor Newman, BP Professor of Information Engineering at the University of Oxford has been writing autonomous vehicle algorithms for 20 years. Since 1999 he has worked on the core ideas that underpin autonomous vehicles worldwide. His work has been fundamental in enabling the operation of autonomous sub-sea vehicles including those that dealt with the Deepwater Horizon oil leak in the Gulf of Mexico.

During an Engineering and Physical Sciences Research Council Leadership Fellowship, Professor Newman developed the 'Robotcar', which in 2013 became the first autonomous vehicle on UK roads, paving the way for future autonomous vehicle operation. His technical work underpins the government's strategy on driverless cars, and he currently serves on the Department for Transport's Science Advisory Council.

Professor Newman co-founded Oxbotica, which has recently partnered with Addison Lee to bring autonomous taxis to London. Its technology enables robots to navigate without relying on GPS or any other external infrastructure. Instead it uses onboard sensors, cameras, lasers and radars to interpret and act in specific environments. Oxbotica's Universal Autonomy software has been used commercially in a vast range of environments – from autonomous cars on public roads to mines, warehouses, forests, airports and ports, in any weather, at any time.

Jo da Silva's career has focused on engineering challenges around infrastructure and resilience of cities © Arup

STRUCTURES FOR A SUSTAINABLE SOCIETY

The growth of megacities and factors such as climate change have changed the nature of the challenges engineers face. Jo da Silva OBE FREng warns of the growing need to consider the resilience of the infrastructure that sustains cities and their inhabitants. She talked to Michael Kenward OBE about her work in sustainable development at Arup, and the lessons she has learned from her involvement in disaster relief.

Jo da Silva worked on the refurbishment of the Royal Geographical Society in Kensington © James Morris

A bus shelter may have seemed like a modest start for an aspiring structural engineer, but Jo da Silva OBE FREng built on those foundations and now applies her engineering skills on a much bigger canvas, as Global Leader for Sustainable Development at Arup. In reality, that bus shelter was a cut above the average, the architect was, after all, Norman Foster OM. Da Silva's role as a structural engineer was to turn the architect's ideas into something that could be built and would last. The bus shelter was the first step in her ambition to, as she puts it, "do something that has social purpose". She now addresses the challenges of the world's biggest cities and their complex infrastructure. "We very much recognise the global environment in which we work and the global challenges that are facing society," she explains, "climate change, rapid urbanisation, and the transition to a digital future."

Few young women choose to become engineers, even today. "We have pretty much the worst figures for female engineers of any country in Europe," da Silva complains. Fortunately, at school she had a clear understanding of what engineers do. "I am sure that the biggest influence on me deciding to be an engineer was because my physics teacher at school had been an engineer." He had worked on an icon of modern engineering, the design of the nose of the Concorde supersonic airliner. With her interest piqued, another school contact arranged for da Silva to visit Arup. She walked into an office full of models of buildings, "just like now," she says, waving to an array of models in Arup's office off London's Tottenham Court Road. "I thought, that looks fun."

After studying civil engineering at the University of Cambridge, in 1989 da Silva worked in India on emergency management. A year later she returned to the UK as a graduate engineer with Arup, where she worked on larger projects such as Hong Kong International Airport and then, thanks to projects backed by the National Lottery Heritage Fund, historic sites in the UK including the National Portrait Gallery and the Royal Geographical Society in Kensington. These developments posed contrasting engineering challenges. Hong Kong was a new site, maybe not quite a green field, but certainly very different from working on listed buildings. Da Silva remembers these heritage projects with affection. The engineers had to work in the confines of historically significant, listed buildings. "I found that really exciting and really challenging. It unlocked a lot of creativity."

These projects fed da Silva's growing appreciation of what Ove Arup, the firm's founder, called 'total architecture'. "Engineering used to be only about technical parameters," she explains. "It has increasingly become about environmental parameters and more and more it is becoming about social parameters. We are realising that how humans interact with what we create and design is part of the overall performance of the system."

DISASTER RELIEF

Today, engineering challenges for da Silva revolve around infrastructure rather than individual construction projects. Again, she draws on her experiences in various natural disaster zones to illustrate the point. As she put it in her 2017 Gold Medal lecture (an award presented to individuals who have made a unique and outstanding contribution to the advancement of structural engineering) at the Institution of Structural Engineers, her career at Arup has been interrupted by "very abrupt leaves of absence" working for various humanitarian and UN agencies in the aftermath of disasters.

One of those 'abrupt absences' involved rushing to Rwanda in 1994 when Engineers for Disaster Relief, now known as RedR (*Ingenia* 35, 'Rebuilding lives in times of disaster'), asked her to help with the aftermath of genocide. Almost overnight, 250,000 refugees created the second biggest city in Tanzania. Da Silva describes seeing urbanisation happening before her eyes. In 2004, the United Nations High Commissioner for Refugees (UNHCR) asked her to take her engineering skills to Sri Lanka to address the impact of the Indian Ocean tsunami. There she coordinated the work of over 100 humanitarian agencies that built over 60,000 shelters in six months.

What might have seemed like diversions from mainstream structural engineering prepared da Silva for the radical change in how we now think about the built environment. Architects, planners and engineers no longer mostly focus on buildings, today they consider infrastructure and its role in society. "Working in developing countries, and particularly in post-disaster situations, you really realise how important infrastructure systems are."

Jo da Silva in Indonesia after the 2005 tsunami, where she coordinated the shelter building efforts © Arup

SUSTAINABLE DEVELOPMENT

Jo argues that thinking about infrastructure in terms of what it does for society, and its impact on the environment and on climate change is essential. "Sustainable development is fundamentally about creating a balance between the needs of an ever-growing population and the health of our planet, and the limited resources that it can provide," says da Silva. "What we are interested in, because our business is the built environment, is how that relates to the business environment, urbanisation and infrastructure."

Da Silva uses air travel as an example of the need for new ways of thinking about infrastructure. With Arup's own pursuit of sustainable development as a 'guiding star', she sometimes gets asked about the firm's work on airports. "You can't necessarily condemn airports as bad," she says. "You need to think about what they do." They play an important role creating jobs, and are part of critical supply chains for medicine and food. They also enable cultural exchange, which contributes to social cohesion. But that does not let airports off the hook: "you could put photovoltaic solar cells on the roof of terminal buildings and make them net energy generators. You can actually improve those roofs, design them differently and harvest rainwater in areas where there are water shortages."

In 2009, as a part of the campaign to change thinking in the industry, da Silva founded Arup International Development as a not-for-profit subsidiary that works with development and humanitarian organisations. The remit for this new business was "to help them make best use of resources in combating poverty and vulnerability, while increasing wellbeing and resilience". Since then, the issues behind that activity have become more mainstream. "When I started the international development business at Arup, the things that I was worrying about, because it focused on the global South, were issues of climate change, rapid urbanisation and inequity. These are now all recognised as global challenges, as relevant in the UK as in Asia."

It was the nature of the firm that made it possible for da Silva to set up the new business. "One of the things that attracted me to Arup in the first place was because social usefulness is a part of its DNA," says da Silva. It isn't all about money. The firm, which chalked up revenue of around £1.5 billion last year, is now held in a trust and is effectively owned by the 15,000 or so staff working across more than 40 countries. Da Silva is one of around 40 Arup Fellows whose thinking guides other staff members and clients.

RISE OF TECHNOLOGY

A lot has changed in engineering since Ove Arup founded the business in 1946. The pace of that change has increased since da Silva joined the firm. Perhaps the most obvious change is the rise of information technology. Da Silva once had to write programs in Fortran to work out how to put one building together. There was even a DEC10 mainframe computer in the basement. However, as she says of her early days, "we all had drawing boards and we did calculations by hand with pencils and paper". There were advantages to this – work could carry on when, as sometimes happened, there were power cuts.

These days, rows of computers sit alongside those models of buildings and developments. The computers have transformed what engineers do. "It was very exciting because the power of computers was enabling us to do things that we couldn't have done before." Da Silva illustrates this with a personal anecdote. "I have always loved shell structures," she explains, "Luigi Nervi was one of my heroes with his concrete shell structures." It was only when computer technology arrived that she could indulge her passion and create single-skin steel lattice structures. These are non-linear structures in how they behave and that meant using some complex computing.

"This shift to digital technology and the use of data, automation, and artificial intelligence is taking us into a whole new era of engineering," says da Silva. Thanks to machine learning, engineers don't have to spend hours on mundane tasks like analysing borehole data. "You don't really want to do things twice. If you can do things once and then automate it, hurrah!" You can do in hours tasks that once took days. As a consequence, she says, "the scale of projects that we can do now is way bigger".

The real benefit of this digital transformation, says da Silva, is that it frees up engineers' time for more creative pursuits. Thinking time has become more important as engineers take on increasingly complex challenges that require a broader mix of expertise. Another big change in da Silva's career has been the need to bring in more disciplines to handle that complexity. "Life isn't just about technical parameters. You need to understand the environmental parameters, the social parameters, the economics behind what we are doing."

EVOLUTION OF ENGINEERING

More generally, da Silva believes that the profession itself has changed. "The discipline of engineering has evolved substantially over the past 30 years. It is not just about technical knowledge and know-how. It is not just our analytical capability, it is also creativity and problem-solving capability." These attributes are essential components of any attempts to solve society's current challenges. "We live in an increasingly complex society that is permanently under stress and facing dynamic hazards such as climate change."

For da Silva, the three key strands in her engineering are sustainability, resilience and inclusivity. "Sustainability, for me, is about the environmental agenda." She takes a swipe at conventional thinking. "An engineer will believe in the second law of thermodynamics. An economist will believe in economic growth." But economic growth exists within a world that is designed by the laws of physics, she adds.

In 2017, Jo da Silva was awarded a Gold Medal from the Institution of Structural Engineers for outstanding contribution to structural engineering © Arup

When it comes to resilience, da Silva is a campaigner. As she sees it, "resilience is about contemplating failure and thinking about what happens when shocks and stresses occur". Engineers need to forget about failsafe and to plan for safe failure. (see box *Resilience in cities*)

Da Silva's view is that we have to accept that failure will happen, but we need to think about it more carefully. "We are required by law to design for a one-in-100-year flood, but we are not required to ask what happens if that one-in-100-year flood is exceeded, and whether failure at that point is sudden and catastrophic or whether it is a much more gentle, progressive, ductile failure."

Da Silva uses seismic engineering to demonstrate a different approach. "We don't know when an earthquake is going to happen, and we don't want buildings just to fall down. We can tolerate them being damaged as long as everyone can get out safely. You might want to design them for higher performance specifications so that actually they can be back in operation very quickly, like a hospital. But that is not how we typically think when we are designing our roads, our electricity distribution systems or water systems."

Inclusivity, the third of da Silva's essential attributes, might once have seemed quirky but, with talk of a growing 'wealth inequality', the issue has become part of the political mainstream. As da Silva puts it, "Lots of people. One planet. How to rebalance that equation." As she saw in Tanzania and as we saw in London's Tottenham riots in 2011, it doesn't take much to disrupt societies, and when society breaks down it affects everybody. Engineers have a crucial role to play in designing environments that reduce the chances of that happening.

"We, as engineers, create the stage set in which the play happens," says da Silva. Again, she draws on her earlier experiences to illustrate this. "When you are working in developing countries, a lot of what you do involves participatory processes to engage with people and understand what they want and what their views are. Those processes are becoming more prevalent here."

Sustainable development, now explicitly embracing inclusivity and resilience, has been the underlying theme of da Silva's career. So much has changed since she worked on bus shelters that da Silva sometimes wonders how she should describe herself. "Do I refer to myself as a structural engineer? That would conjure up in people's minds someone who sits and designs buildings on a day-to-day basis." She has contributed to designing buildings over the past 10 years, but admits that she hasn't designed a building herself in that time.

However, she insists, her approach hasn't changed: "I'm still using the way engineers think in terms of the ability to define problems, to ask the right questions, and to assemble information and think creatively in all the work that I do."

BIOGRAPHY

Michael Kenward OBE has been a freelance writer since 1990 and is a member of the *Ingenia* Editorial Board. He is Editor-at-Large of *Science|Business*.

RESILIENCE IN CITIES

Over the three decades since Jo da Silva started work as a structural engineer with Arup, she has become increasingly interested in the resilience of the infrastructure that sustains society. More recently, she has placed a growing emphasis on the resilience of cities: "the population of the world has more than doubled in my lifetime. The urban population has more than quadrupled."

The people who live in these cities depend on infrastructure that is, says da Silva, "planned, designed and constructed by engineers". We expect the infrastructure to protect us from such natural events as storms and landslides and to provide essential services such as water and energy. "We rely on infrastructure to connect the places in which we live, to enable the flow of goods and services and for people to get around to go to work, go to school." It does not take much to disrupt these activities.

Cities have become an important focus for work on resilience, says da Silva. She puts this down partly to the effect of Hurricane Sandy, which wreaked havoc on New York City in October 2012. It was a wake-up call and one that has helped propel growing analysis of cities, such as the work of the Rockefeller Foundation and its 100 Resilient Cities programme.

Da Silva says that "what really matters is that we understand that infrastructure faces these threats, called shocks and stresses. When we design infrastructure systems we should recognise the possibility of such events occurring and the dependency on other systems."

Among other roles, da Silva is the acting director of The Resilience Shift, "a very exciting initiative, supported by the Lloyd's Register Foundation". The aim of this initiative is to raise awareness of the need for infrastructure to be resilient.

Da Silva has also worked closely with the Rockefeller Foundation to spread resilience thinking and to devise ways of measuring resilience. With support from the foundation Arup helped to develop the City Resilience Index. This established 12 goals that cities should aim for to achieve resilience.

One way of describing the challenge is, in da Silva's words, that "resilience is really about the ability of that system to continue to operate when bad things happen". It includes the things that we can anticipate and try to predict but "also the things that you can't predict or because life is changing. The suite of hazards due to climate change is changing. The complexity of the cities that we live in is changing."

Some of the thinking around resilience may seem counterintuitive. In an era when everything is increasingly digital, and with much talk about 'smart cities' shouldn't digital technologies be a way of reacting to nasty things? "If we design systems that are too reliant on digital technology and feedback loops, what happens if the technology goes down?" da Silva asks. "Perhaps it makes us more vulnerable not less vulnerable."

Resilience is a complex issue that encompasses many factors. For example, da Silva has worked on how we respond to flooding and coastal development as we seek to create resilience. "If you look at flood defences, we would have defaulted to 'build a seawall'. Now, if you look at coastal engineering and what we are doing, there are much more integrated solutions that make the most of the environmental features, whether those are mangroves or dunes. You combine the natural blue and green infrastructure with physical grey infrastructure, and it is how those two things actually work together that matters."

Then there is transport, which is one of the fastest growing areas at Arup. Here too the need for resilience requires new ways of thinking. As da Silva said recently, "We talk about bridges and roads when we should be talking about mobility, connectivity and ensuring the flow of goods, services and people." For example, says da Silva, the UK's ports are privately owned while the roads and railways that carry cargo to and from them are under public control. "The ports don't talk to each other and they don't have very much sway or interconnection with the planning system." By contrast, Antwerp and other ports in Europe are mostly state-owned.

It is this sort of systems thinking that underpins da Silva's work and her thinking on resilience. "It is shifting from thinking about what we build as an asset, in terms of what it is, and thinking about it in terms of the role that it plays in society and what it does."

CAREER TIMELINE AND DISTINCTIONS

Born, **1967**. Graduated with an MA in civil engineering from the University of Cambridge, **1988**. Graduate engineer at Arup, **1989**. Co-founded RedR International, **1995**. Visiting Senior Research Fellow, University of Cambridge, **2001**. Senior Shelter Coordinator UNHCR after Sri Lanka tsunami, **2005**. Founded Arup International Development, **2009**. Fellow of the Royal Academy of Engineering, **2009**. Appointed an OBE, **2011**. Awarded the Gold Medal of the Institution of Structural Engineers, **2017**.

ECHO-LOCATION FOR NAVIGATION

The Sixth Sense is a handheld device that uses echo-location and haptic feedback to help people with visual impairments and blindness get about safely.

The Sixth Sense hopes to replace the white cane and make navigation easier for people with visual impairments © Hope Tech +

Brian Mwenda grew up in Kenya and attended an integrated school where he studied with people with disabilities. After studying electrical and electronic engineering, he knew that he wanted to use his skills to develop mobility solutions for his friends with visual impairments. He set up a small lab at home and created his first product, The Sixth Sense. The device aims to give people the freedom to walk around independently.

There are almost one million people with visual impairments in Kenya. The Sixth Sense is a handheld instrument that uses echo-location to detect objects up to four metres away. It uses sound waves in an inaudible frequency to detect obstacles: a form of echo-location based on the same principle that bats and dolphins use to move around their environment. Brian's innovation uses ultrasonic sensors to send out sound waves and pick up the reflected ones when they encounter an object. Factoring in the period between sending the wave and the time it is received, the speed of sound in air, the nature of the reflected wave and other factors, the device can formulate information about obstacles and relay this back to the user through haptic feedback.

A white cane is still the most common navigation tool used by visually impaired people, but one of its drawbacks is that it doesn't detect obstacles above the knee. The Sixth Sense will alert users to obstacles that they could collide with, anywhere from their head to their feet. The user is alerted by vibrations, with different vibrations signifying different objects.

Objects on the ground will create a different vibration to those that are directly in front of the user or overhanging, and the intensity of haptic feedback increases as the user gets closer to obstacles. The device can also differentiate between people and obstacles. In crowded places, it will recognise a group of people and the vibrations will be toned down to let the user know that they are in a busy street, while still alerting them to other objects with a higher intensity vibration.

The Sixth Sense uses a GPS Internet of Things system, allowing the user to send a pre-chosen contact person their coordinates if they need assistance. The instrument is fully operational as a stand-alone gadget but can be paired with a mobile app to increase the processing power and offer navigation guidance. The app uses machine learning to acquire user patterns and offer the best routes to use based on the reason a person is moving – the route suggested for rushing to a meeting may be different from that for a casual stroll.

One of the main challenges that Brian's company, Hope Tech +, had to overcome was sourcing the hardware and components for his innovation. Brian collaborated with people across the world who worked on aspects of the product using the materials available in their countries to save time and accelerate product development. Most of the early work was done in Kenya, where 3D printing enabled the team to quickly test different shapes with users. Trials were carried out in the UK, which was where most of the software refinement data was collected. The work came together in Melbourne, where the final product is being refined.

The Sixth Sense device was shortlisted for the 2018 Africa Prize for Engineering Innovation, and Brian took part in HRH The Duke of York's Pitch@Palace event. The Sixth Sense is due to be launched in East Africa, Australia and the UK in the next 18 months.

For more information, visit **www.hopetechplus.com**

HOW DOES THAT WORK?

KETTLE SWITCH-OFF

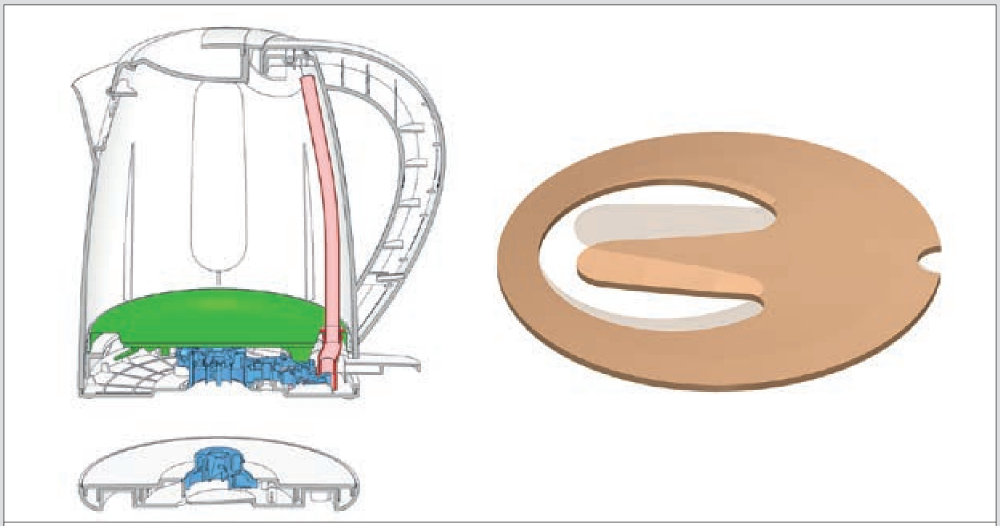
Used every day by millions of people across the world, electric kettles use a surprisingly simple method to overcome a long-standing problem: how to switch themselves off.

When a kettle is plugged into an electric outlet and switched on the electric current flows through a metal coil, which is situated either within or under the water. The coil is, in effect, a heating element and its resistance (the material's efforts to stop electricity flowing through it) turns the electrical energy into heat.

Because a kettle is a sealed unit, the temperature rises quickly within and pretty soon the water boils. So far, so simple. The main problem with the electrical kettle concept has always been how to enable it to switch itself off. In the past they didn't and many a hotel was evacuated when a left kettle boiled and boiled and set off the room's smoke detectors.

Now, all electric kettles have an automatic shut-off that stops heating the water when they reach boiling point. Many of the devices that make this happen are based on an invention by a UK engineer, John Crawshaw Taylor OBE FREng. The problem he faced is that a simple thermostat won't achieve the best result and ensure that the water has fully boiled.

The boiling point of water changes depending on altitude or the amount of impurities in the water, so a thermostat that stops boiling the water at exactly 100°C presents a problem. At sea level, water boils at 100°C, but for every 150-metre increase in elevation, water's boiling point lowers by approximately 0.5°C. If you fancied a cup of tea on the shores of the Dead Sea your kettle would cut off before the water reached boiling point, whereas if you fancied your brew on the top of a mountain, your kettle would never cut off and would boil all the water away.



(left) The green area shows the heating element, when the water boils, steam travels down the steam tube (in red), actuating the bimetallic disc (right) in the blue safety control that disconnects the power supply © Strix Ltd

The ingeniously simple solution to the problem comes in the form of a two-layer bimetallic (a metal with two different thermal expansions) disk that 'flips' at a specific temperature, similar to a metal jam-pot lid that 'pops' out when you open a new jam pot.

The larger-thermal-expansion disk is bonded to a smaller-thermal-expansion one, so that as the temperature rises the combined disk curves so that the faster expanding disk is on the outside, and vice versa as it cools. The cleaver shape of the disk provides a cheap and effective thermostat that snaps suddenly at a certain temperature rather than just bending slowly as it heated.

Another clever feature is that the thermostat is not in the kettle water at all and thus is not tripped by the water temperature, which as established earlier, may not always be 100°C. Instead, it is outside the water and is tripped by a rapid temperature rise induced by the steam that is produced only when the kettle boils.

A channel within the kettle, typically inside the handle, carries steam from the top of the boiling interior down to the thermostat (often near the base), where the temperature rises very rapidly from around ambient to near 100°C as soon as boiling starts. This causes the disk to snap and disconnects the power. The thermostat can now be set to trip whenever the water boils, even if this occurs at different temperatures. If, after the kettle has finished, you listen for a while as it cools you may hear the disk flipping back.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