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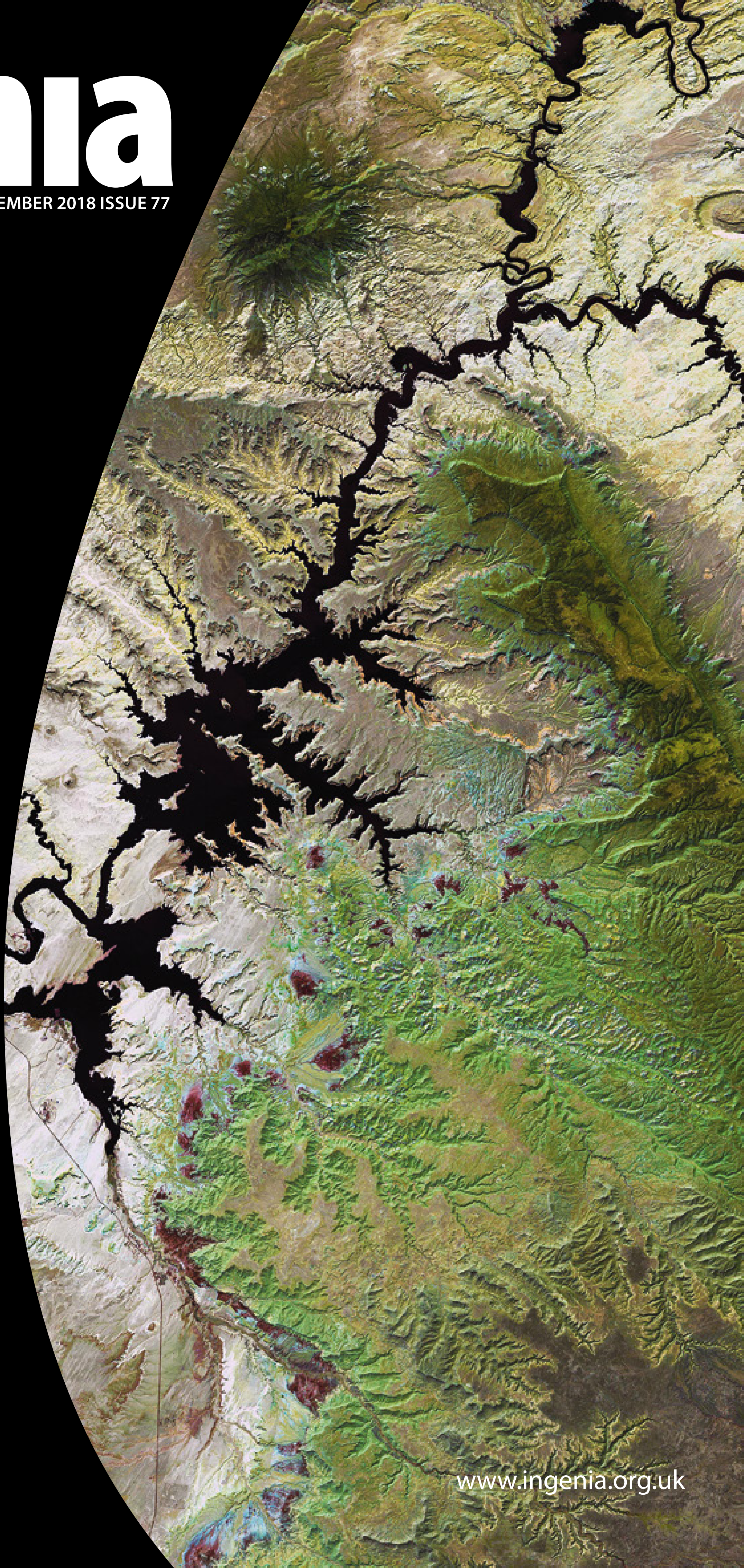
DECEMBER 2018 ISSUE 77

BUILDING A BASEMENT
FORMULA ONE FRIDGES
SLIDING FOOTBALL PITCH
SATELLITE IMAGE ANALYSIS



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Front cover
Landsat image from July 2011 shows Lake Powell, a reservoir on the Colorado River in the US
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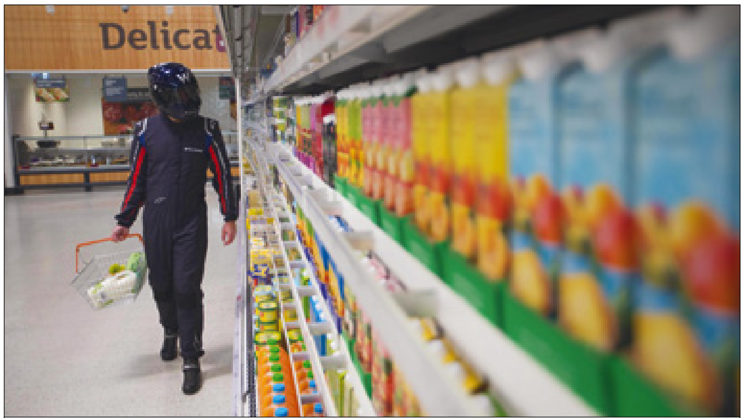

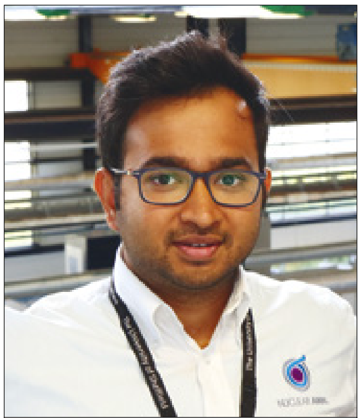

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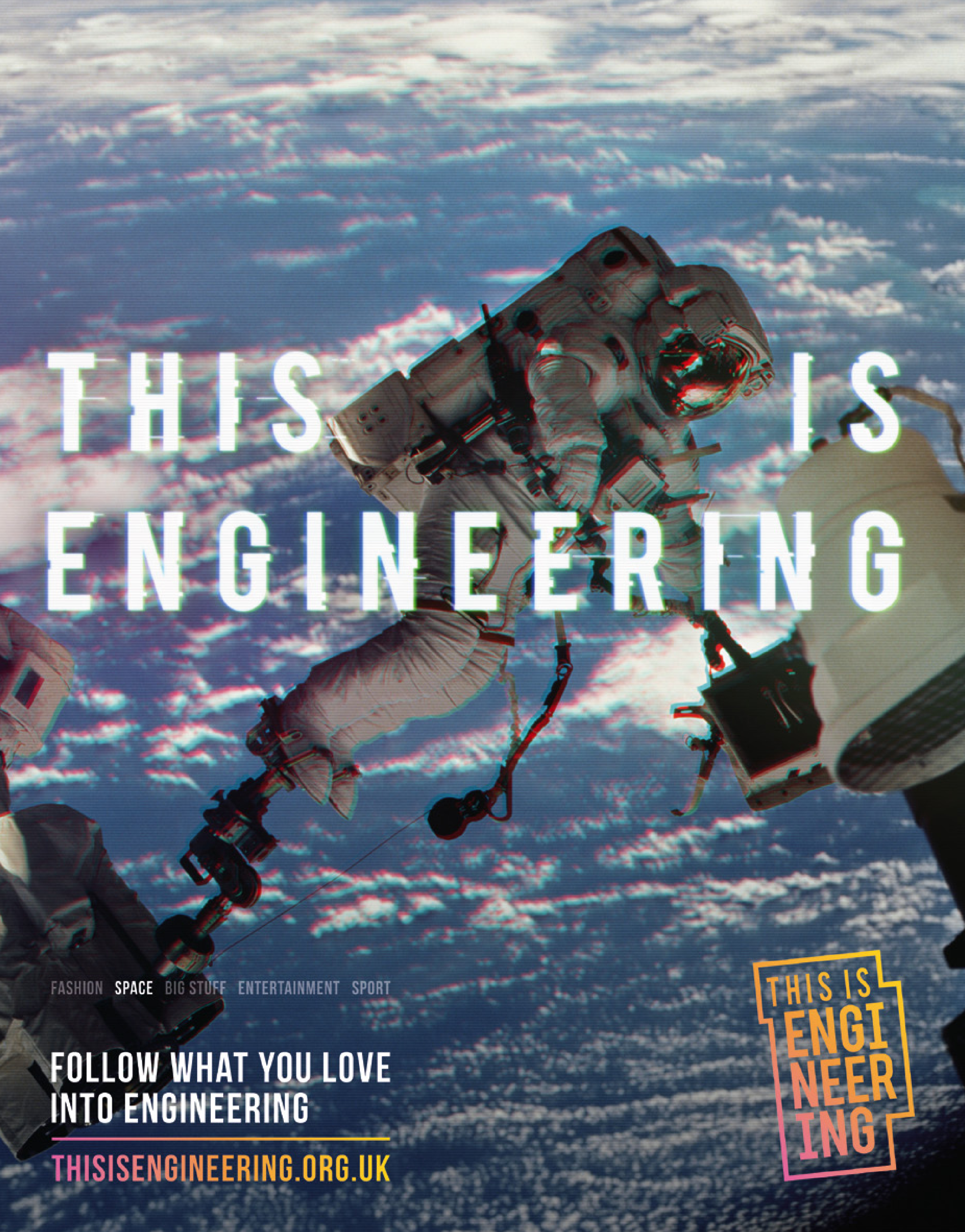
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EDITORIAL

REMOVING GREENHOUSE GASES

Dr Scott Steedman

Engineering the removal of carbon dioxide from the atmosphere is essential if we are to meet the targets laid down in the 2015 Paris Agreement for reducing greenhouse gas emissions. There is an overwhelming scientific consensus that, in the fight against climate change, the world cannot rely on simply reducing carbon dioxide (CO_2) emissions. We need to remove greenhouse gases from the atmosphere directly. Published in September, an important report from the Royal Academy of Engineering and the Royal Society, *Greenhouse gas removal*, presents an ambitious plan setting out how the UK can lead the way in deploying such technologies so that the country is carbon neutral by 2050.

The idea of greenhouse gas removal (GGR) is not new, but technology development, let alone implementation, has been painfully slow. Government and industry urgently need to understand the effectiveness and cost of full-scale GGR projects so that the UK can devise a robust strategy for developing and implementing the technologies.

One of the technologies that will play a critical role in GGR is carbon capture and storage (CCS). CCS involves removing carbon from carbon-rich gases, often pre- or post-combustion at power stations, and storing the CO_2 underground ('Carbon capture and storage', *Ingenia* 27; 'Underground coal gasification', *Ingenia* 43).

The history of CCS in the UK has not been promising. In 2012, the Department of Energy and Climate Change (now part of the Department for Business, Energy and Industrial Strategy) launched a competition to support CCS technologies to extract and store CO_2. The programme was cancelled in 2015, despite proposals for full-scale trials in North Yorkshire and Aberdeenshire. Meanwhile, other countries are making real progress. The Academy's report cites two projects, one in Canada and one in Texas, that are at the demonstration stage and many others are reported to be in operation or under construction worldwide.

There are other ways to remove CO_2 from the atmosphere, but their capacity is limited. The most obvious GGR technique that the UK could implement immediately is increased forestation and wetland development. The largest wetland element could be restoration of salt marshes around the coast. Carbon could also be captured in soil by adapting farming practices on cropland or grassland. But there is limited land available. Even if the area of forestry land in the UK increased by over a third, to 5% of the total land area, the report suggests that this would contribute less than 12% of the UK's 2050 target for CO_2 removal. We need other ways to meet that target.

The built environment is an obvious place to look for ways to store carbon. Using more wood in construction, such as timber-framed housing, would be an easy win. Concrete is a major source of CO_2 emissions in the construction industry where a net carbon saving could be achieved by using different aggregates or novel chemistries for cement production. But again, the total achieveable contribution is likely to be low, around 4% of the UK target.

Other ideas are still at an early stage. One proposal is to spread silicates, potentially derived from industrial waste, on arable land as rock dust, which would react with carbon dioxide in the atmosphere and accelerate natural soil weathering. However, it will take extensive research, development and field trials before this could be licensed.

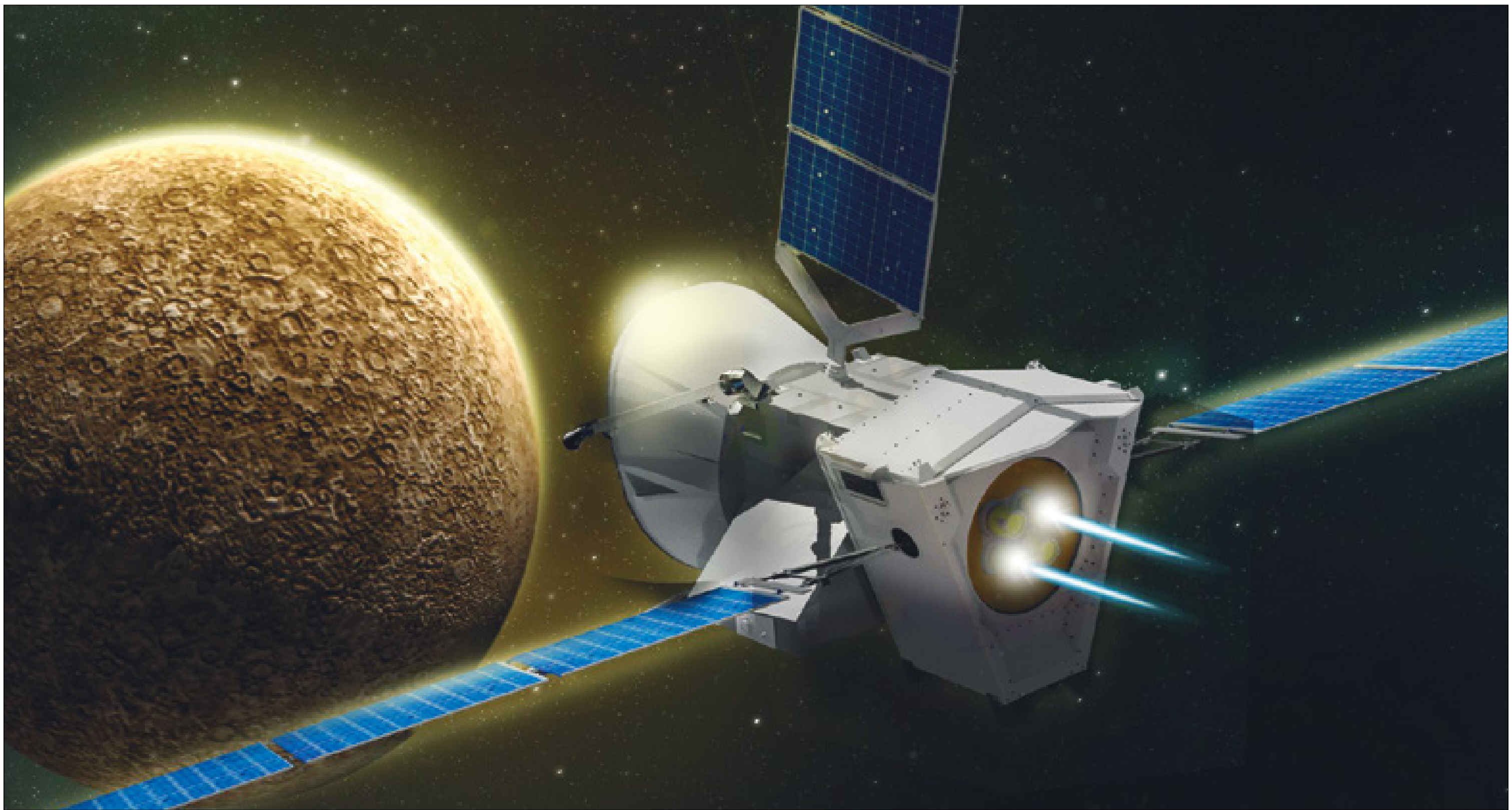
It is clear that if the UK is to meet its 2050 targets, reducing carbon emissions will not be sufficient. Removal of CO_2 from the atmosphere is also essential. Most of this reduction will have to be achieved by using CCS, contributing up to 60% of the total target. The favoured approach is to deploy CCS on biomass power plants, with plants generating energy by burning agricultural, forestry or municipal waste, bringing a double benefit. However, the Academy's report concludes that even this will not be enough and that CO_2 may need to be extracted directly from the air. Pilot projects are already operating in other countries but, as with CCS, not in the UK.

In turbulent political times it is difficult to keep an eye on the long term, but ignoring the problem of climate change is unlikely to lead to a cost-effective outcome for industry and society in the UK. Government needs to heed this important report and urgently re-open the file on CCS.

Dr Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

UK-BUILT SPACECRAFT BOUND FOR MERCURY



An artist's representation of the BepiColombo satellite © Airbus

The European satellite BepiColombo has been successfully sent on a seven-year voyage to Mercury, the smallest and least explored planet of the inner Solar System.

On 20 October, the 6.4-metre-high satellite, which weighs four tonnes, blasted off atop the European Ariane 5 rocket from Europe's spaceport in Kourou, French Guiana.

The satellite, which has been partially built in the UK by Airbus, will provide data about Mercury's internal structure, the composition of its surface and the evolution of its geological features, including craters around the planet's north pole that are known to contain ice. The mission will also study Mercury's magnetic field and measure how it interacts with the solar wind – a stream of highly charged particles coming from the Sun.

The spacecraft, only the third in history to visit Mercury, has been developed jointly by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). It consists of two orbiters that will circle Mercury at different altitudes and provide complementary data through their combined 16 instruments.

The Mercury Planetary Orbiter (MPO), developed by ESA, carries 11 instruments, including the British-built Mercury Imaging X-ray Spectrometer – a novel optical instrument that will analyse small features on the planet's surface and determine their composition.

Since Mercury orbits only 58 million kilometres away from the Sun, the orbiters will be exposed to extremely high temperatures. Airbus engineers have therefore designed and built a special shield for the MPO that covers the side of the spacecraft carrying the instruments. The shield consists of 49 layers of ceramics and aluminium that protect against the heat.

The second orbiter, the Mercury Magnetospheric Orbiter, has been developed by JAXA. It will collect data about the planet's magnetosphere and its interaction with the solar wind.

The two orbiters travel to Mercury stacked on top of the Mercury Transfer Module, which propels the entire spacecraft on its journey using an innovative electric propulsion system that uses a stream of electrons to generate thrust.

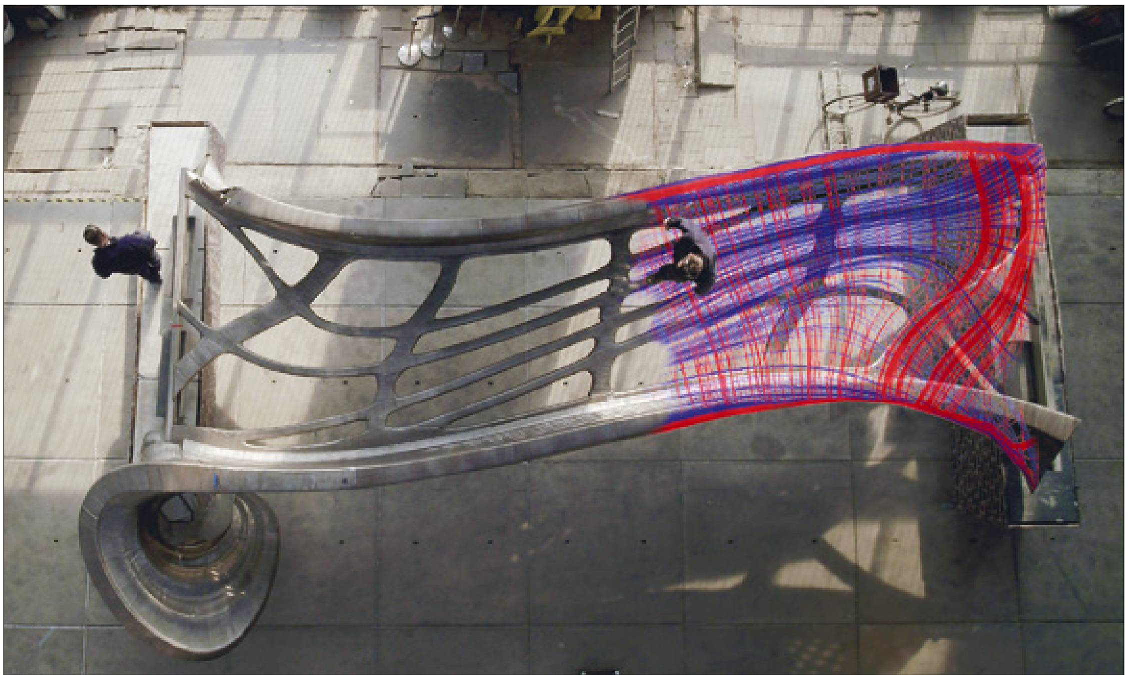
Words: Portia Sale and Tereza Pultarova

THE WORLD'S FIRST 3D-PRINTED STEEL BRIDGE

A consortium, which includes Arup as lead structural engineer, has created the world's largest, single-span, 3D-printed bridge from layers of printed steel.

In 2019, the 12-metre bridge will be installed over the Oudezijds Achterburgwal canal in Amsterdam. It took about a year for robotic manufacturing technology startup MX3D to print the bridge at its workshop in the city. Six-axis robots, which have greater flexibility, built the bridge with programmed robotic arms controlling large-scale welding machines.

As well as being the first bridge to be 3D printed in steel, data scientists have designed it as a 'living laboratory'. The bridge is covered in a network of sensors that generate data about everyone that crosses it, as well as about the bridge itself. The data will be fed back to a 'digital twin' of the bridge developed by the Alan Turing Institute and Arup, which will help to analyse the data on bridge traffic, structural integrity and the surrounding environment. The data will provide insights into how the new material and construction process behaves, and will contribute to the future of safe, data-driven engineering.



Stress analysis visualisation produced by the project's engineering partner Arup superimposed on a photo of the bridge © Arup and Joris Laarman Lab

A team at Imperial College London has been collaborating with colleagues in several academic fields to develop a long-term structural health monitoring network to ensure that the bridge remains safe throughout its lifetime.

Liam Butler, from the University of Cambridge's Centre for Smart Infrastructure and Construction, elaborated: "Thousands of people are going to cross this bridge an hour, so the City of Amsterdam is interested at looking at things like foot traffic, CO_2 emissions, noise and decibel levels, and more."

Mark Girolami, the Alan Turing Institute's Programme Director for Data-Centric Engineering, added: "3D printing is poised to become a major player in engineering, and we need to develop novel data-centric approaches for testing and monitoring to realise its full potential. When we couple 3D printing with digital twin technology, we can then accelerate the infrastructure design process, ensuring that we design optimal and efficient structures with respect to environmental impact, architectural freedom and manufacturing costs."

A 3D-printed concrete bridge previously opened in the Netherlands in 2017.

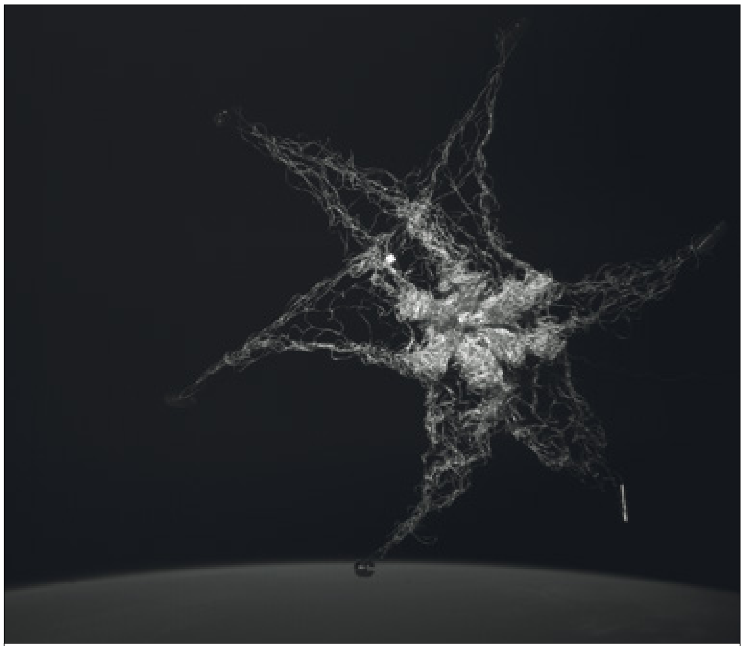
REMOVEDEBRIS MISSION SUCCESSFULLY TESTS NET

In September, the RemoveDEBRIS mission successfully used its net to capture a deployed target that simulated a piece of debris in orbit.

Launched in early 2018, the RemoveDEBRIS mission is the first experiment to test technologies to remove space debris in low Earth orbit ('Mission to remove space debris', *Ingenia* 72). It is estimated that there are more than 7,600 tonnes of space junk in and around Earth's orbit, risking collisions with satellites.

Professor Guglielmo Aglietti FREng, Director of the Surrey Space Centre, said: "We are absolutely delighted with the outcome of the net technology. While it might sound like a simple idea, the complexity of using a net in space to capture a piece of debris took many years of planning, engineering and coordination between the Surrey Space Centre, Airbus and our partners – but there is more work to be done. These are very exciting times for us all."

In the coming months, the RemoveDEBRIS spacecraft will test more debris removal technologies, including a vision-based navigation system that uses cameras to analyse and observe potential debris, and harpoon capture technology. A drag-sail will then bring the debris back into the Earth's atmosphere where it will be destroyed, in compliance with international debris regulations.



The RemoveDEBRIS spacecraft released its onboard net to successfully capture a piece of simulated space debris © University of Surrey

DRILLING STARTS ON UK'S FIRST GEOTHERMAL ELECTRICITY PLANT

The geothermal electricity plant will host what is thought to be the deepest hole ever drilled in the UK © Geothermal Engineering Ltd

In November, work started on building the UK's first deep geothermal electricity plant in Cornwall. It aims to demonstrate the potential of geothermal energy for electricity and renewable heat in the UK.

Two deep geothermal wells will be drilled at the site, the deepest of which will reach 4.5 kilometres, the deepest hole ever drilled in the UK. A pump will extract water from the well at a temperature of approximately 19°C, before being fed through a heat exchanger at the surface. It will then be re-injected into the ground to pick up more heat from the rocks in a continuous cycle. The heat will be converted into electricity and supplied to the National Grid. The demonstration plant will deliver up to 3 megawatts of electricity, which is thought to be enough energy to power around 3,000 homes.

Geothermal energy is low carbon, renewable and a continuous energy source. The UK's geothermal resources have the potential to supply up to 20% of the UK's electricity and heat energy in a reliable and sustainable way.

The project is being funded by the European Regional Development Fund, Cornwall Council and private investors, and delivery partners include GeoScience Ltd, The British Geological Survey and the University of Plymouth Sustainable Earth Institute.

JOIN IN WITH THE YEAR OF ENGINEERING

2018. THE YEAR OF ENGINEERING

JANUARY 2019
THIS IS ENGINEERING SEASON THREE

In January, *This is Engineering* season three launches with films showcasing engineers working in exciting areas. To see the new films, visit **www.thisisengineering.org.uk**

FUTURE ENGINEERS

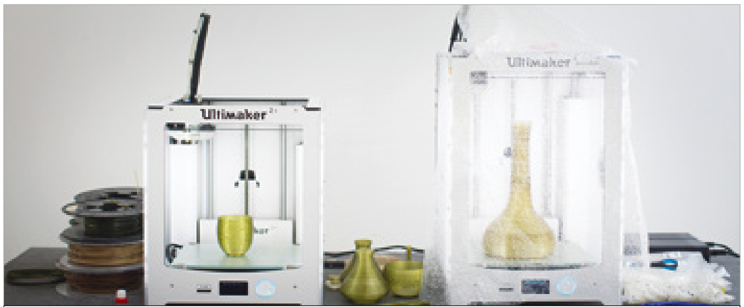
London Transport Museum's new gallery inspires an interest in STEM subjects and asks visitors whether they're a dreamer, planner or fixer. Visitors can drive an Elizabeth line train simulator, plan a greener and happier city, and scan their palms with the latest ticket technology.
www.ltmuseum.co.uk

Future Engineers at London Transport Museum © London Transport Museum

2019
WOMEN'S ENGINEERING SOCIETY CENTENARY

2019 marks the centenary of the Women's Engineering Society (WES). Throughout 2019, WES is asking people to support national, regional and local events to celebrate women engineers and the technologies they have developed.
www.wes.org.uk/wes-centenary

An engineer in the BBC's engineering department in 1941 © WES and IET archives



3D-printed algae © atelierLUMA Florent Gardin

NOW TO 6 JANUARY 2019
BEAZLEY DESIGNS OF THE YEAR 2018

The Design Museum's annual exhibition celebrates innovative and exciting concepts and designs across fashion, architecture, digital, transport, product, and graphic design. Nominations this year include products 3D printed with algae, a self-healing electronic skin, Virgin Hyperloop One, and SpaceX's Falcon Heavy rocket.
www.designmuseum.org

13 TO 16 MARCH 2019
THE BIG BANG

The annual Big Bang fair in Birmingham is the UK's largest celebration of STEM for young people. Visitors to the fair can get hands-on at a range of workshops and exhibits, or take part in STEM shows.
www.thebigbangfair.co.uk

The Big Bang

HOW I GOT HERE

Q&A

DR RAHUL MANDAL
NUCLEAR ENGINEER

Dr Rahul Mandal is a Research Associate in the Nuclear Advanced Manufacturing Research Centre (AMRC) at the University of Sheffield, and winner of *The Great British Bake Off* 2018. His research includes cleanliness inspection of nuclear components, surface metrology and residual stress measurements using electronic speckle pattern interferometry.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

From quite an early age, I was interested in finding out why and how everything works around me. I have to thank my parents for tolerating the immense amount of questions I asked growing up. This is what science is: the desire to learn how nature and surrounding things work.

In a way, the science behind baking and cooking also drew me to that. I was astonished by how you can take the same ingredients but with different proportions, and create a completely new dish. I don't want to sound clichéd but I do think that science is behind everything we do.

HOW DID YOU GET TO WHERE YOU ARE NOW?

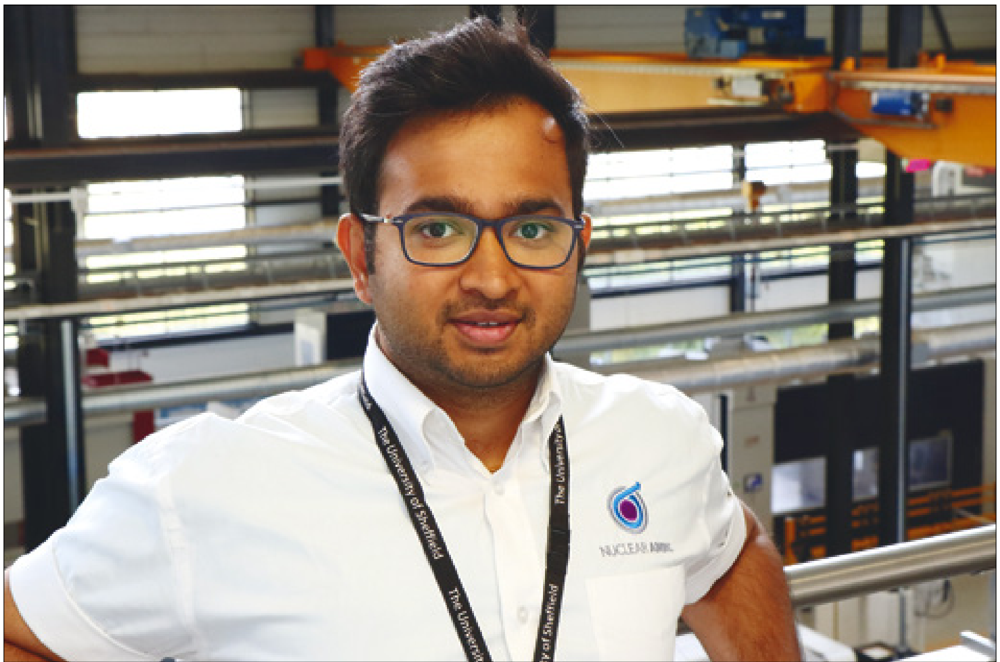
My undergraduate degree was in electronics and communication engineering. I enjoyed my course but was drawn more towards communication engineering, especially optical communications. That led to my master's, which was in optics and optoelectronics from the University of Calcutta, India.

I then came to the UK to study for my PhD in Optical Engineering from Loughborough University – my thesis was entitled 'Calibration and adjustment of coherence scanning interferometry' (interferometry is a measurement method that uses the phenomenon of wave interference). During the final year, I did a small project on the optical sensing and characterisation of red blood cells.

I started my current position at the Nuclear AMRC almost straight after graduation. My research primarily involves investigating the cleanliness of nuclear components to identify any contamination or flaw that could lead to failure during its in-service life. I'm developing new techniques in light-based metrology, including automating the inspection process. Working in the nuclear industry is very interesting, because I know that my work will help deliver safe, low-carbon energy for decades to come. I am really proud to be a part of it.

As a child, I liked to sit down and read a book, paint, or watch cookery or science programmes. My mum was scared to let me cook, so I didn't really cook anything until I was 15. I started cooking every day after I moved to the UK about eight years ago, out of necessity almost. I was still nowhere near baking at that point. I had never used an oven in India, so I was scared of ovens. I learned from my housemates how to operate it and slowly progressed in the world of baking.

I baked my first cake in 2016 and brought it into work for my birthday. Pretty much all my cakes have been taken into work. I wasn't ever really exposed to British baking before, so feedback from colleagues has been really important. It's been a steep learning curve from my first cake two years ago to what I do now.



Dr Rahul Mandal joined the Nuclear Advanced Manufacturing Research Centre as a Research Associate after graduation. His work includes developing automated inspection techniques for large nuclear components such as heat exchanger tubesheets.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

I have to say that completing my PhD was definitely the biggest achievement, but participating in *The Great British Bake Off* is something that I will always remember. It was a journey that made me learn a lot more about myself.

I always mention that baking is a science. It shows how simple ingredients such as flour, water, salt, and yeast can transform into one of humankind's staple foods. With the addition of sugar, butter and eggs, you can make the world's favourite sweet treats. Changing the proportion of the ingredients will make the most varied form of pastries. People will say it's magic – I would say it is pure science.

I learned a lot during my time in the *Bake Off* tent. Seeing so many people work harmoniously together to make one programme work is amazing. It taught me to push my boundaries. In a normal situation, I would never attempt to make a biscuit chandelier at home. But, along with my fellow bakers, I managed to do it, which is, in my words, a combination of science and engineering.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

The best thing about engineering is that I can find out and understand how something works. I can design things that will solve a problem, and work on improving their performance until they work in just the way I want.

I am also a volunteer STEM Ambassador, and really enjoy working with young aspiring students to inspire them to develop their own career in science and engineering. There is a huge gender imbalance in the field of science and engineering and, for different reasons, a huge part of the female population is not encouraged enough to take science and engineering as subjects in school. I would like to say to everyone – boys and girls – that if you can cook and bake, you can do science and engineering.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

There's not really a typical day at the Nuclear AMRC. I normally work on multiple projects for various customers, so I have to follow certain plans so that the projects are completed to schedule. Usually I like to distribute my weekly time into different projects and work accordingly. One day, I might be setting up laser interferometry experiments in the laboratory, the next I'll be using digital cameras to create a detailed three-dimensional image of a testpiece that's just come off one of our giant machine tools.

However, during the weekend, I'm busy planning my new bakes and probably experimenting with new flavour combinations. It is really busy, but I like to be busy. The diversity of the projects also keeps me going.

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

Enjoy your subject, love your job and never stop questioning. When you work in engineering, you have to think ahead. You have to think about the issues that might arise, and then try to deal with them.

WHAT'S NEXT FOR YOU?

To be honest, I am not sure. I love science and engineering, so I would love to carry on with my research work. I will definitely carry on baking – and I would love to combine the two. I want to inspire young school students to do more science and engineering, as well as to do more baking and cooking. For me science and baking are synonymous. If you can do one, you can do the other – you just need to put some love and care into learning how to do it.

QUICK-FIRE FACTS

Age: **31**

Qualifications: **PhD MTech BTech**

Biggest engineering inspiration: **Nature, which has produced the biggest scientific and engineering creations – it inspires me to try and do something new every day.**

Most-used technology: **Anything used to measure is my type of technology: from a rule and measuring scale to high-end interferometric measurements.**

Three words that describe you: **Scientific, bashful baker.**

OPINION

COLLABORATION IS KEY FOR DEGREE APPRENTICESHIPS

Apprenticeships are often seen as a less prestigious route into engineering than university study and a degree. However, with the introduction of placements that include a bachelor's or master's qualification, this looks set to change. Richard Hamer, Education and Skills Director at BAE Systems, believes that closer partnership between key stakeholders presents a real opportunity to make degree apprenticeships a great success.

Richard Hamer

It's disappointing that the number of people starting apprenticeships last year had fallen by over 130,000 from the previous 12 months, a drop of 25%. However, I do think that this is only a temporary glitch while companies, large and small, get to grips with the new system, one that includes the exciting possibility of degree apprenticeships, which offer both education and industry training.

Engineering has always supported apprenticeships, even when the rest of society fell out of love with them. In many respects, apprenticeships have always been a part of engineering. As far back as the Middle Ages, the apprentice worked with the master in a whole range of early 'engineering' fields, from smithing and swordmaking to saddlery.

Many senior engineers across the aerospace and defence sector, including BAE Systems, and more broadly across engineering chose the apprenticeship route into the profession. Many Fellows of the Royal Academy of Engineering began their careers as apprentices, including Past President Sir John Parker GBE FREng, a titan of engineering industry, who started his career as a Harland and Wolff shipyard apprentice in the 1950s ('Engineering success', *Ingenia* 48).

Of course, it was right that apprenticeships should be reinvigorated and expanded beyond the engineering sector. It is also welcome that government, the wider business community and education establishments are working together to change the perception of apprenticeships as a second-class education option to university.

However, since the early part of this decade one major requirement resulting from the new focus on apprenticeships has been to ensure that the high quality of training that is provided to engineering apprentices is replicated across the board. The introduction of shorter apprenticeships across various industries in the early 2010s, where existing employees were placed on so-called 'apprenticeships' of only three months did not help to present a respected and credible skills pathway. Fortunately, the government put a swift

We know that young people who start their careers with us will be just as good as graduates who join us several years later

stop to these and apprenticeships are now required to be a minimum of one year's duration. Nevertheless, to put it in context, the engineering community places even more importance on the robustness of apprenticeship routes into the profession with most apprenticeships lasting at least three years and degree apprenticeships continuing to five years.

The reform of the apprentice delivery system has, as with any major new initiative, not been without challenge, as the policies on work-based training have evolved. Some industry leaders have found the process of developing and approving new standards with the newly formed Institute for Apprenticeships (IfA) protracted and complex and, as a consequence, some apprentice training programmes have been delayed, although the IfA is now committed to a faster and more efficient approval process. Technical issues around holistic end-point-assessment have also been difficult to implement.

The recent introduction of the Apprenticeship Levy for all companies in England with a wage bill over £3 million has also faced criticism from industry leaders, who say that accessing the fund is overly complex, bureaucratic and inflexible. Business organisations such as the CBI, Institute of Directors and EEF, the manufacturers organisation, have argued that it has deterred companies from taking on apprentices. Further concerns around the maximum funding allocated for apprenticeships is disadvantaging companies in high-cost sectors such as engineering, and the three million target set by the government is prioritising short duration apprenticeships in lower value sectors. Yet despite these challenges, I believe that employers are still very supportive of the principle of apprenticeships and are looking to work with government and the IfA to address these challenges constructively and make the new system work successfully.

The recent announcements from government in the 2018 Autumn Budget are also welcome news for businesses offering apprenticeships. The increasing flexibility for large employers to transfer up to 25% of their levy funds to their supply chain businesses will do much to improve the number of young people starting apprenticeships.

In common with many leading engineering businesses, BAE Systems has long been committed to apprenticeships. We know that young people who start their careers with us will be just as good as graduates who join us several years later, and of course, the apprentices have the benefit of several years' industrial experience. All our experience shows us that, as we invest in our apprentices through high-quality training and professional development opportunities, apprentices return this to the business through dedication, commitment and high performance in the workplace.

Recently, the government introduced degree apprenticeships as an exciting new addition to the education landscape and at BAE Systems we have embraced these opportunities fully. In the past, apprenticeships have ended at HNC, HND or Foundation degree, which are equivalent to qualification levels 4 and 5. Degree apprenticeships push on-the-job training provision a step further to include bachelor degree (level 6) and specialist master's degree (level 7). For the first time, this enables individuals, young or old, to achieve a degree while working – combining the best of cutting-edge industry training with world-leading university education.

But are degree apprenticeships really as academically rigorous as standard, full-time university degrees? From my experienced industry perspective, I would say an adamant yes, and what's more, I would go further and say that many of our degree apprentices outshine graduates who have come through the traditional degree route. Without the exposure to vocational, industry relevant challenges, traditional university education will always find it difficult to fully meet the needs of business. This view, shared across industry, may well lead to a very different landscape in higher education in the future – and one that is developed in partnership between higher education and engineering employers. Indeed, the Aerospace and Airworthiness Apprenticeship Trailblazer Group has, for example, worked closely with a number of universities such as Cranfield, Sheffield and Kingston to develop new standards.

Despite the difficulties, I believe that government and businesses share the same fundamental belief in the enormous value of apprenticeships to individuals, business and the economy. By working together to iron out issues the UK can continue to deliver the high-quality training that our nation needs.

BIOGRAPHY

Richard Hamer is Education and Skills Director at BAE Systems. He has responsibility for BAE Systems' education, apprenticeship, graduate and skills activities at a corporate level. Richard has worked for BAE Systems for 14 years and before that he was Head of Education at BT. BAE Systems has around 2,000 apprentices in training, and of the 538 apprentices it recruited in 2018, 164 are higher/degree apprentices.

LETTERS

HAVE SOMETHING TO SAY?
EMAIL US: editor@ingenia.org.uk

SMALL MODULAR REACTORS ARE KEY TO DECARBONISED ENERGY

The re-emergence of hydrogen as a major source of renewable energy induces a feeling of déjà vu ('Back to the future with hydrogen', *Ingenia* 76). Hydrogen was the major constituent of coal gas, later town gas, which was piped all round the country to provide lighting and heating through the 19th and 20th centuries, albeit at a low pressure of four inches water gauge in the units of the day. It has a very high burning velocity compared with natural gas, so when the great switch to natural gas occurred in the 1960s and 1970s, after the discovery of large quantities of natural gas in the North Sea, all combustion appliances had to be changed, a massive undertaking achieved by Sir Denis Rooke OM CBE FREng FRS of British Gas (a Founding Fellow of the Royal Academy of Engineering). I remember the changeover in my rambling terrace house was achieved by three specially trained, out of work, former orchestral string players.

The prospect of safely switching back to hydrogen, with its dangerously wide flammability limits of 4% to 75% by volume in air compared with 5% to 15% for natural gas, is a daunting prospect. But in the field of transport, hydrogen feeding a fuel cell to provide electric traction for both road or rail is a very attractive proposition, provided one is not too concerned about a 'fuel tank' containing hydrogen at pressures of more than 90 million pascals.

In the 1980s, when the idea of electric taxis was ahead of its time, I drove an electric black cab a few miles around London, powered by a hydrogen-air fuel cell with the hydrogen stored in a heavy standard metal cylinder lying on the back seat. Nowadays, a high-pressure hydrogen tank onboard will give a range of 500 miles.

What is contentious is the source of the hydrogen, which must be carbon free if it is to achieve energy decarbonisation, as the editorial points out. Hydrogen is produced commercially by steam reforming of natural gas, but this process produces carbon dioxide that must then be subject to carbon capture and storage, which would be very expensive and is as yet unproven. Electrolysis of water or steam using 'clean' electricity would be a better bet. Renewable energy, such as wind or solar, could make a contribution, if the wind is blowing strongly over the UK, for example, the spare electricity could be used for hydrogen production.

Not mentioned in the editorial is clean nuclear power using the latest high temperature small modular reactors (SMRs). They can break down water thermally to hydrogen at high temperature, without having to resort to electrolysis. They generate electricity very efficiently with an availability of over 90% (unlike renewables) but can also produce carbon-free process and domestic heat. Conventional pressurised water nuclear reactors do not have this versatile ability to produce clean heat as well as electricity and 80% of our energy requirement is for heat and transport, not electricity.

SMRs will have to play a leading role if we are to decarbonise energy by 2050, but this will require government support. There is currently a competition being run by the Department for Business, Energy and Industrial Strategy to choose the best SMR technology, but government will have to assist with the expensive licensing process before potential investors will move to fund a fleet of much needed high-temperature SMRs.

Professor Ian Fells CBE FREng FRSE

DIGITAL SKILLS WILL PREPARE THE WORKFORCE OF THE FUTURE

In response to the article in September's *Ingenia* outlining the challenge of the digitally left behind community (DLBC) ('Supporting the digitally left behind', *Ingenia* 76), I wanted to first praise the authors for highlighting the issues and suggesting practical steps that we, as an engineering community, could take to address the issues raised, while recognising that the issue is not limited to the engineering community but wider society. Furthermore, I wanted to acknowledge that the piece also recognised that systems engineering has a job to do on many of the platforms and applications that we are exposed to as a necessary part of our increasingly online life. There is no doubt that this kind of approach would be enormously beneficial but it does require, in my view, a much more integrated, ambitious and urgent focus on the skills of the workforce and the population in general. While many systems could be re-engineered for better usability, there is still a huge percentage of the population who are apprehensive about the use and integrity of systems and much of that is because they lack the basic skills, training and expertise to engage effectively. This is also true in the supply side where it is reported there are, according to The Tech Partnership and other skills-based bodies, shortages of up to a million skilled IT professionals, over the next five to ten years. The very people able to create those next generation systems are also in short supply.

It is urgently important that we skill the general population as well as the existing workforce. If two thirds of 2030's workers are already in the workforce today, out of full-time education and critically short of digital skills, this is not a problem that we can leave to schools or universities. As businesses, we must address the reskilling of the existing workforce with the help of government.

Work by Be the Business, the organisation created by business to address the chronic productivity lag in the UK, has identified that, alongside leadership skills, the distinct lack of digital skills limits the adoption of new productive digital ways of working. As a key shortfall of the UK economy, this leaves the UK languishing at the bottom end of the productivity scale of the G7 nations and some 15% to 17% behind the average.

There are hundreds of skills initiatives, funded by public and private money, that could be used to help with this reskilling challenge, but they are largely uncoordinated and can be extremely confusing to the average citizen or worker. We need to find a way of radically simplifying the landscape and aligning efforts, such that individuals and companies have a clearer path to upskilling, reskilling and acquiring the relevant skills for the next generation. The Royal Academy of Engineering can play an important part in that simplification and alignment. There have been several attempts to provide this kind of coordination, such as the Department for Digital, Culture, Media and Sport's Digital Skills Partnership and the skills initiatives in many sector deals, but even they are challenged in corralling some of the fragmented pieces. *Made Smarter*, the engineering industry and industrial sector's initiative to help to provide a much greater use of digital technologies to improve productivity, has identified the need to simplify access to, and help with navigation of, the skills system as a key objective of the soon-to-start pilot in North West England. This initiative will hopefully address all levels of workers and citizens wishing to reskill and upskill, from the digitally elite to the DLBC. It will try to amplify existing excellent initiatives such as Movement to Work, which focuses on those not in education, employment or training, and charities that are part of the digital skills partnership.

Reassuringly, the article states the need to understand both the size and challenge of the DLBC, which I think is absolutely right and will allow us to focus more on issues of design and accessibility, often seen as unrelated to engineering, which will benefit everyone. Once again, we need to make sure we crowd-in as much existing work as possible, such as the excellent work led by Sarah Weir OBE at the Design Council and Innovate UK's funding of projects to further design in all aspects of life, from cities to healthcare.

In summary, I welcome the focus on designing and building accessible systems and the need to understand the real issues further. However, I would suggest that if we really want to crack the issue of demand as well as supply, we need to have a coordinated, ambitious and dynamic push on reskilling and upskilling the existing population and workforce. This should not be done by creating a whole load of new initiatives but by crowding in and coordinating the myriad of initiatives that many find so confusing today.

Phil Smith
Former Chairman of Cisco UK
Chair (designate) of IQE Plc
Chair of the Digital Skills Partnership

The football pitch at the new Tottenham Hotspur Stadium hides an artificial NFL field underneath. The pitch slides over in three metal trays, each weighing over 3,000 tonnes, which are stored beneath the stands when not in use © Tottenham Hotspur / SCX Special Projects

THE FOOTBALL PITCH IN THREE PIECES

Tottenham Hotspur Stadium is part of a regeneration project that has transformed the stadium and surrounding area. As well as being home to Tottenham Hotspur Football Club, the stadium will host NFL games in the UK, and to accommodate both sports, the stadium boasts the world's first dividing sliding pitch. Science journalist Richard Gray asked Danny Pickard, lead engineer at SCX, how the pitch was developed.

For 118 years, White Hart Lane, home of Tottenham Hotspur Football Club, has been one of the most famous addresses in football history. The stadium hosted some of the team's most dramatic moments, from famously picking apart the formidable Polish side Górnik Zabrze in its first ever European Cup appearance in 1961 to defeating Inter Milan during its first Champions League outing in 2010. In total, Spurs played 2,533 competitive games at the North London stadium before demolition work began in May 2017 to make room for a new 62,062 seat stadium. This redevelopment, rumoured to cost around £850 million, has not only almost doubled White Hart Lane's previous capacity, but has also turned it into one of the most flexible major venues in the world. At the very heart of the stadium, the pitch has been transformed from a simple patch of grass into an ambitious engineering project.

Matches at the new Tottenham Hotspur Stadium will be played on the world's first dividing, retractable grass football pitch. Mounted in three enormous trays, the grass surface can be rolled away beneath the south stand to reveal an artificial NFL American football field beneath. The Premier League Club already has a 10-year contract with the NFL to stage a minimum of two games a season, using the artificial surface. The retracting pitch means that the stadium can quickly convert from hosting a football match on the grass pitch to an NFL game on the artificial field in just a few hours. The hard-wearing artificial surface also means that the stadium can host other events, such as concerts, without damaging the grass. For most football grounds hosting concerts and other events involves putting thick matting onto the pitch, which can quickly kill the grass and requires new turf to be laid before the

RETRACTABLE PITCHES AROUND THE WORLD

While the Tottenham Hotspur Stadium now has the first retractable pitch that divides into sections before it is rolled away, it is not the first stadium in the world to have a removable grass field.

In 1998, the first major sports stadium to get a so-called 'convertible pitch' was the GelreDome in Arnhem, Netherlands. Home to the football club Vitesse Arnhem, a huge concrete tray that contains the turf can be pushed out through an 85-metre opening under the south stand to make way for concerts and other sporting events. It takes around three and a half hours to move the enormous slab and it is usually left outside the stadium in the wind, rain and sunshine so that the grass can grow.

In 2001, retractable pitches were installed at both the Arena AufSchalke football stadium, which is now known as the Veltins-Arena, in Gelsenkirchen, Germany, and at the Sapporo Dome in Toyohira-ku, Japan. The 11,000-tonne playing field at the Veltins-Arena, home of the Bundesliga side FC Schalke 04, can take six to eight hours to move in or out of the stadium. Four hydraulic presses push the lawn about half a metre at a time in what can be a 340-metre round trip.

The Sapporo Dome primarily hosts baseball and football games for the Hokkaido Nippon-ham Fighters and Consadole Sapporo FC. The pitch here is the world's first 'hovering football stage', where the 8,300-tonne field partly floats on a cushion of air as it moves, reducing the weight that the 34 wheels underneath have to carry. To convert the stadium, the artificial baseball field rolls away and a bank of seats are retracted into the walls. The pitch rolls into the arena and rotates 90 degrees along with a revolving bank of seats until moved into place, and the retractable seats move back into place. In total, the whole process can take four or five hours.

Most recently the 63,400-seat University of Phoenix Stadium in Glendale, just west of Phoenix, Arizona, opened in 2006. It makes use of the space outside the stadium, rolling the 9,300-tonne grass playing surface out through an opening at one end in around one hour. This has allowed the stadium to host events as diverse as motorsports, wrestling matches, NFL games, international football matches and concerts by acts including Beyoncé, Taylor Swift and U2.

The whole pitch weighs over 9,000 tonnes, more than the Eiffel Tower in Paris. Each of the three sections need to fit together seamlessly so that fans watching football games, and footballers taking part, cannot tell that matches are happening on trays mounted 1.6 metres above solid ground

Extensive testing of the sliding pitch prototype was undertaken at Tottenham Hotspur's training centre in Enfield © Tottenham Hotspur / SCX Special Projects

next match can be played. This can take days, if not weeks, for most stadiums.

The football club turned to Sheffield-based engineering firm SCX to help deliver the retractable pitch. SCX specialises in complex kinetic architecture having previously created the enormous retractable roof over Centre Court and No.1 Court at Wimbledon. It also built a 900-tonne section of removable turf at Ascot racecourse that is wheeled out of the way to reveal an access road to the paddocks in the centre of the track so that vehicles do not damage the race course. However, despite this previous experience, the stadium's new retractable pitch has been one of the most challenging projects the firm has undertaken.

The columns that support the terracing underneath the south stand meant that the pitch could not roll out from beneath as a single entity, as has been done with other retractable pitches around the world [see box on the previous page]. Instead, SCX opted to split the pitch into three lengthwise sections that divide roughly along the outer edges of the penalty box.

Once this concept had been agreed, the club tasked its Head of Moving Structures Nick Cooper FREng and his team with designing and fully integrating the moving pitch, surrounds and supporting services into the stadium build programme.

Each section is mounted on rails that are hidden beneath the NFL pitch, which allow them to be rolled in and out of position through a complex set of manoeuvres from under the south stand. First the central section rolls in and then the outer sections pull alongside and move inwards to meet the central piece.

JOINING THE PITCH

The whole pitch weighs over 9,000 tonnes, more than the Eiffel Tower in Paris. Each of the three sections need to fit together seamlessly so that fans watching football games, and footballers taking part, cannot tell that matches are happening on trays mounted 1.6 metres above solid ground. Ensuring the accuracy required to get this kind of join along the entire 118-metre-long edge was one of the most difficult aspects of the project for the engineering team. Each section, composed of 33 metal trays welded together from 16-millimetre-thick steel plates, needs to line up perfectly when brought together.

During fabrication, the trays were bolted together in the exact same order and under the same conditions to control the effects of heating and cooling, caused by the welding, making the steel buckle and bow in different ways. The team built a test site at Tottenham Hotspur's training centre with a section of movable turf to experiment how the pitch would fit together. With a length of 21 metres and a width of 3 metres, this gave the team a more manageable replica of the edges to experiment with.

The team discovered that the best way of ensuring a reliable and repeatable joint was to have the trays 'touch' via a three-ply rubber strip running down the entire length of each section of pitch, just beneath the turf. Alternatives included a plastic mesh that would allow the roots to knit through over time. The engineers at SCX also tested how best to pull the pitch apart again as, when the sections are joined, the grass can become entangled as roots and leaves grow. The team initially used a device similar to a pizza cutter to slice between the sections, but it left noticeable damage when the pitch was reassembled later. Instead, it found that the best approach was to simply let the turf tear naturally as the sections pulled apart, allowing it to split along its own weak points.

To ensure that each section would line up, the first tray module in each was surveyed into place to make sure it was correctly aligned, before the other trays were bolted alongside. When complete, the trays were lined with a waterproof layer before matting, gravel and soil were put on top. Then the turf itself was rolled out over the top.

ON THE MOVE

Sixty-eight electric motors power every second tray in each section, with the ones on the centre rail doing most of the work, and the motors on the outside rails powering opposing wheels, running diagonally opposite. Together, they give each section a top speed of seven metres per minute. Once the goals, advertising boards and pitch surround are removed, it takes two people just 25 minutes to roll the pitch away.

To switch from one event to the other can take just four hours. As the pitch is rolled away, one operator walks in front of the moving section while another, the 'watcher', observes the pitch's progress. Moving the pitch sections requires both operators to continually press down their safety buttons. An automatic slow-down system is triggered as the huge pitch sections trip sensors when the sections are 75 centimetres apart. This slows the movement down to the tenth of its top speed – just seven centimetres per minute – before triggering a second and third sensor that brings the whole structure to a halt. The motors themselves can be used to slow and brake the pitch while it is moving.

Once it has stopped, a parking brake – similar to the one in a car – is applied to clamp the structure in place. The outer sections then move inwards to meet the centre of the pitch with the help of 32 hydraulic cylinders on the steel structure underneath.

There needs to be enough space to allow this to take place, so the team created touchlines that move too. Along the length of the pitch, touchlines are mounted on top of a huge steel structure with artificial turf bonded to the surface. Six-metre-wide flaps on the inside edge of this structure can be lifted or lowered using hydraulic actuators.

Once the pitch is in place, hydraulic cylinders raise the sidelines before the flaps are lowered to rest on the edge of the turf. Ramps in each corner of the pitch also pivot upwards with the touchlines to give access from beneath the stands. Then the entire structure is locked into place. At the north end of the stadium, a third set of flaps hides a series of growlights and sprinklers that can be wheeled out over the pitch between games

A computer-generated image shows how the three trays carrying the pitch will slide over the artificial NFL field below
© Tottenham Hotspur / SCX Special Projects

The integrated grow lighting system at the new stadium is a moving structure that weighs approximately 120 tonnes with 864 individual lights covering a total of 7,525 square metres. It is lifted hydraulically onto rails mounted permanently on the east and west pitch trays and then seamlessly rolls from one end of the pitch to the other. This enables full coverage of the pitch without equipment ever coming directly into contact with the grass surface © Tottenham Hotspur / SCX Special Projects

to give the grass some extra light and water. There are six giant trusses, each carrying 126 growlights, that span the entire width of the pitch and weigh just under 20 tonnes each, which can be rolled out on a rail hidden underneath the touchline. Hydraulic ramps on either side allow the height of these to be adjusted so that the amount of light the grass receives can be tuned.

To cope with any unexpected failures, the entire project has large amounts of extra capacity engineered into the structure. For example, just 20 motors are needed to move the pitch into place, less than a third of the number that have been installed. Each motorised module has been wired together in a way that helps prevent the structure from becoming stuck. Module 2, for example, connects to module 12 rather than the next one in line so that if there is a power failure in module 2, it does not affect the motor beside it and the sliding mechanism will still work. Meanwhile, there are movable dummy powerlines behind the movable touchlines that run from east to west, so that if the power system fails on one side, it can be run from the other. The hydraulic cylinders that are needed to lift the flaps and the touchlines are also interchangeable, so that they can be swapped if there is a failure.

FLEXIBLE BUT STABLE

With something of this size raised off solid ground, there was a danger that it could behave very differently from standard football pitches. Running on a large steel structure suspended above the ground will cause it to bounce, so the team faced the challenge of making sure the whole structure did not turn into a giant trampoline. A bouncy pitch could affect the way that players move or jump for a header, how goalkeepers leap to make a save, or the way the ball bounces, and would have interfered with the whole game. The team fitted a series of accelerometers around a football field during a game to monitor vibrations and find out how a normal pitch behaved. Engineers also tested a movable pitch at the University of Phoenix Stadium in Glendale, Arizona, during a match between Real Madrid and LA Galaxy to work out what the optimal resonant frequency should be. Widening the main structural beams allowed the engineers to tune the pitch to the right frequency, so that it feels like solid ground.

While the structure needed to be solid, it also had to be flexible. Changes in temperature could cause the steel frames to expand and contract, meaning the pitch can grow or shrink by up to 45 millimetres in all directions. To cope with this constantly changing size, engineers designed the 598 wheels that support the pitch sections so that they do not slip off the rails as it moves. Each section of pitch runs on three rails, and the wheels on the central rail have a flange on both sides to keep the trays running in a straight line. However, the wheels running down the outer rails have no flange, allowing them to move left and right across the rail as the weather conditions shift.

The front wheels of each pitch section have also been

When the NFL pitch is in use, the touchline structure lowers to ground level and the flaps sit flush on the side of the artificial pitch. When the pitch sections are ready to be rolled in, the flaps can be raised into a vertical position at the touch of a button © Tottenham Hotspur / SCX Special Projects

fitted with steel scrapers and brushes to clear the rails of any dirt or debris that might get washed down onto the rails. While a waterproof liner seals the pitch trays to prevent any sand or soil spilling down onto the rails, bad weather can wash debris under the pitch, meaning this cleaning mechanism is essential. An integrated watering and drainage system in the pitch ensures that the grass can get the nutrients it needs to grow without making the ground beneath waterlogged. The systems can be quickly disconnected when the pitch needs to be moved. When the pitch is stored under the stands, LED lights provide the grass with just enough light to stay alive but not enough to cause it to grow. A ventilation system also pushes air over it to prevent it from becoming too hot, cold or damp.

ALWAYS PREPARED

Over the years, SCX has learned that an 'over engineering' strategy is the key to success in this sort of large moving project, because it is hard to know exactly what obstacles might need to be overcome when it is operating. It pays dividends to have extra capacity in hand.

SCX finished installing the pitch in October 2018 – just over six years since it first started working on the project – and the first matches are set to be played in 2019.

This feat of engineering may mean that the stadium will become almost as famous for its world-first pitch, as it is for its football team.

The retractable pitch passes its first tests in May 2018 during the building of the stadium © Tottenham Hotspur / SCX Special Projects

BIOGRAPHY

Danny Pickard joined SCX Special Projects as a design engineer after graduating in 2007. He has delivered a wide range of mechanical handling and specialist crane solutions.

To watch how the pitch works, please visit
www.youtube.com/watch?v=JmeljNpIV1k

Williams Advanced Engineering and Aerofoil Energy collaborated on an innovative yet simple technology to reduce energy usage in supermarkets – as well as making the chiller aisle a more pleasant experience for shoppers © Williams Advanced Engineering

WARM RESPONSE TO FLUID DYNAMICS

Technology that makes racing cars go faster is now saving energy in supermarkets and reducing the 'frozen aisle' effect often found near the chiller cabinets. Michael Kenward OBE spoke to Paul McAndrew, CEO of Aerofoil Energy, and Christian Bedford, Head of Legal at Williams Advanced Engineering, about how an established engineering company and a startup business worked together to bring this new engineering to the market.

Engineers know that they are on to something when their innovations provoke the response: "Why didn't someone think of that before?". That was certainly the response from some people when in 2013 Paul McAndrew, CEO of Aerofoil Energy, started looking for backing and engineering input for his idea for saving energy in supermarkets. There was clearly enough new engineering in the concept to get Aerofoil Energy's technology on to the shortlist of three finalists for this year's MacRobert Award ('MacRobert Award 2018', *Ingenia* 75).

McAndrew's simple aerofoil concept can make a significant difference in supermarket refrigeration, an important area of business, as well as benefiting the environment through energy savings. Shoppers also experience welcome relief from the 'frozen aisle' effect, the Arctic feeling that comes over anyone who navigates the chilled-food section in a supermarket.

Building on his career in refrigeration, McAndrew had his eye on the energy bills that supermarkets rack up keeping produce at the right temperature in the cabinets that store frozen and chilled food. Supermarkets and convenience stores account for an estimated 10% of the UK's total energy use, with fridges using around 40% of that, and a lot of that energy is wasted when cold air flows out of the cabinets.

Most supermarkets use open-fronted refrigerator cabinets for better merchandising and to give customers easy access. Current designs launch a cushion of cooled air at the top of the cabinet, intending to recapture it at the bottom. In practice, a lot of cold air escapes and warm air seeps in, increasing the temperature of the return air. Cold air also flows out into the surrounding aisles, to the discomfort of shoppers. Some supermarkets then put extra heaters in those aisles, compounding the problem.

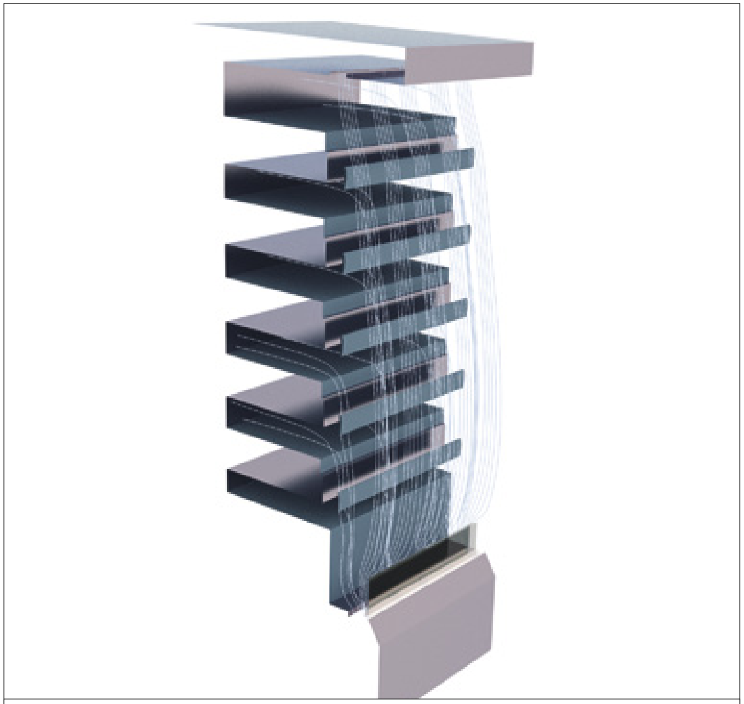
ENERGY SAVED

- Sainsbury's alone accounts for 1% of the UK's total energy demand.
- Refrigeration can account for more than half of the energy costs of running supermarkets and convenience stores.
- Applying the principles of an aerofoil, extending forward from each shelf in a refrigeration unit, contains and re-energises the downward flow of cool air in open refrigerators.
- Each fridge fitted with an aerofoil uses 15% to 25% less energy than those without.

BUILT ON EXPERIENCE

McAndrew spent around 20 years in sales of refrigeration cabinets and says that "should we or shouldn't we use doors?" was a constant question he heard from customers. His answer was always: "I really don't know". Although they can save energy, closed-door fridges are more expensive to make, harder to recycle and have high maintenance costs, as well as being difficult to open for elderly or frail people, or those with a basket in one hand.

With so many people seeking his advice, it made sense for McAndrew to investigate the issue; he came up with the idea of using aerofoils to control the air curtain in a fridge and to maintain its stability. It helped that he is, as he confesses, "also a bit of a geek", and had a lightbulb moment when watching a video of smoke going over an aerofoil in a wind tunnel. An aerofoil is a structure with curved surfaces designed to give the most favourable ratio of lift to drag in flight, and is generally used as the basic form of the wings, fins and tailplanes in most aircraft. A similar design is present in the front and rear



Acting as the price label holder, the aerofoil maintains a cohesive and conforming cold-air curtain, ensuring that the cold air cascades down the fridge and preventing its escape into the aisle © Williams Advanced Engineering

wings of a Formula One (F1) car. The idea that an aerofoil could bend a moving stream of air was exactly what he felt was needed for an air curtain on a fridge to stop the air from drifting over into the aisles in the supermarket.

McAndrew could not get the idea out of his head. He commissioned a fabricator to make some aerofoils and created some hand-made fittings. He then borrowed a fridge and carried out experiments at an independent centre that ran tests for fridge-makers under industry standard conditions. When McAndrew rang to find out how it had gone, the test centre broke the news that it was rerunning the tests. Fearing the worst, he asked if that meant the tests had failed. Far from it, the results looked good, almost too good to be true. "They got quite excited," he reports.

To save McAndrew money, the test lab initially modelled the aerofoils with computational fluid dynamics (CFD), which again showed such promise that they were quickly tested on a fridge with impressive results.

EXPERTISE AND INVESTMENT

In 2014, McAndrew set up Aerofoil Energy to bring the idea to market and took to the internet to look for help and investment. He was not sure whether to take it seriously when an email arrived from Williams F1 racing. Christian Bedford, a Director of Williams Technology Ventures, says that McAndrew "nearly put the phone down", when he rang to discuss the idea. In McAndrew's defence, he explains that he did not know about Williams's work outside F1. "You do realise that this is a supermarket fridge operation," he recalls asking. "Are you sure you have contacted the right person?"

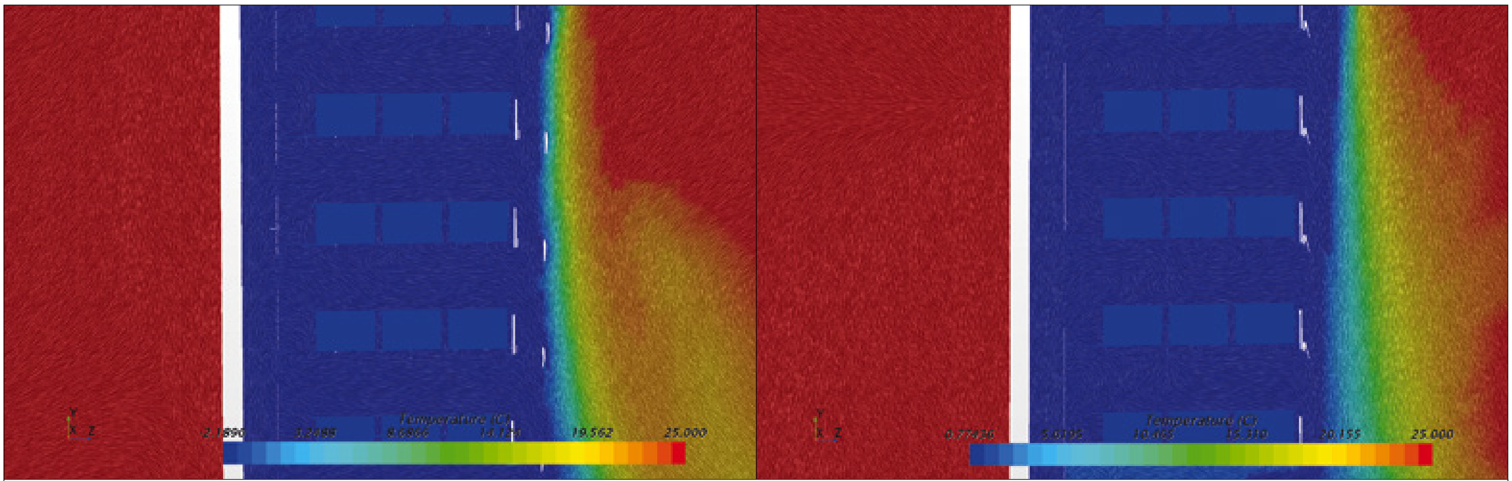
In reality, the project fitted in nicely with Williams's plans to broaden its activities beyond F1. Set up in 2012, Williams Advanced Engineering exists to take the technology, know-how, intellectual property and what Bedford dubs, "the culture of innovation from four decades in F1" and aims to translate that across several industries.

Bedford says that it was the title of McAndrew's message that caught Williams's attention. It said, "the big four need these". The big four in question were the UK's biggest supermarket chains.

After the initial disbelief, McAndrew realised that Williams's expertise could help develop the aerofoil technology. His idea was about modifying airflow in open fridges to create an air curtain, while F1 racing cars also depend heavily on aerodynamics. Williams has a large team of aerodynamics engineers, with two sophisticated wind tunnels and powerful expertise in CFD, not to mention access to serious supercomputer facilities. McAndrew could see that work on the fins on F1 racing cars might be relevant to the control of airflow in fridges.

Getting the right fittings were essential to the development of the technology. There isn't much value in something that looks great if engineers cannot retrofit it to existing fridges, and Aerofoil Energy and Williams's work on fixtures added to the patent portfolio that protects the technology
© Williams Advanced Engineering

Williams took McAndrew's aerofoil and put the shape through further CFD analysis. There then followed a year of work on the shape of the aerofoils, refining and perfecting what McAndrew admits were his "pretty rudimentary" designs, based on aerofoils that he



The image on the left shows a fridge fitted with an aerofoil and demonstrates that more of the cool air is retained, compared the image on the right, which shows a fridge with no aerofoil fitted © Williams Advanced Engineering

saw in YouTube videos and elsewhere.

CFD analysis led to more laboratory tests at Williams that proved that the aerofoils were extremely effective. "We have what we believe is possibly the most aerodynamically perfect piece of equipment that you can move air around a fridge with," says McAndrew. "It was worth the partnership just for that." Bedford adds: "We proved that by using a particular shape of aerofoil we could demonstrate up to 30% energy savings for supermarket fridges."

Getting the shape right was just the beginning. Aerofoil Energy had to come up with a design that did not get in shoppers' way or make it difficult for shelf stackers to replenish supplies. There was also the challenge of fitting aerofoils to existing fridges with a minimum of disruption to a busy supermarket.

Williams's engineering expertise came to the fore when it addressed the challenge of attaching aerofoils to fridges. The engineers turned to additive manufacturing (also known as 3D printing) to make parts of the aerofoil and to try different designs for brackets to attach aerofoils to fridges. "One of the key things we needed to achieve was a low fit-out time," says Bedford. "Technicians have to go into the supermarket, fit the brackets and then attach the aerofoil." Williams devised a variety of bracket designs to reduce the time it takes to retrofit fridges in a supermarket. These days, supermarkets specify that new fridges they buy come with aerofoils fitted.

Aerofoil Energy tested its approach on this front when it started adding 'fins' to chiller cabinets at Sainsbury's. It took about three months to adapt half of the supermarket's cabinets. "It has been really well received," says McAndrew. Engineers cannot just turn up drilling holes in shelves. Retailers certainly want to save energy, but they do not want anything happening that could disrupt customers. "We spent an awful lot of time perfecting that side of it as well," McAndrew adds.

ENERGY SAVING

All this works because Aerofoil Energy can demonstrate energy savings, although McAndrew is careful not to make exaggerated claims. Carefully controlled tests in standardised environments have achieved savings of as much as 38%. However, as he quickly points out: "we get a huge range of results from stores. These go from around 10% all the way up to about 25%." McAndrew's line is that anything over 10% for refrigerator energy savings in a supermarket: "is a very big number".

Sainsbury's is certainly happy to back this view in its endorsement of the technology. One of the first to adopt the new technology, the supermarket's annual energy bill runs to hundreds of millions of pounds and refrigeration accounts for about half of that amount.

TIMELINE

February 2013 – Paul McAndrew conceives idea of using aerofoils to save energy in commercial open fridges.

November 2013 – formation of Aerofoil Energy.

September 2014 – Williams Advanced Engineering scouts Aerofoil Energy.

April 2015 – collaboration starts with Williams Advanced Engineering.

May 2016 – more than 50 independent laboratory trials by over 20 of the world's largest refrigeration manufacturers.

January 2017 – first units begin to be installed.

November 2017 – Sainsbury's announces plans to install Aerofoil across its stores, which it has now completed.

March 2018 – trials in over 1,000 stores.

June 2018 – one of three finalists for Royal Academy of Engineering's MacRobert Award.

September 2018 – Asda announces installation in an additional 187 supermarkets.

October 2018 – more than 400,000 aerofoils fitted in over 1,500 stores to date.

The aerofoil technology can deliver significant energy and carbon savings for supermarkets, as well as other benefits such as improving product temperature, meaning that less chilled food is wasted © Williams Advanced Engineering

The supermarket believes that aerofoils have cut refrigeration costs by up to 15% – a potential annual saving of several million pounds.

On the wider front, open fridges add significantly to the UK's energy consumption. Sainsbury's alone accounts for about 1% of the UK's energy bill. Warmer aisles not only cut the bills, there is also a chance that customers will spend more time, and money, in previously chilly aisles.

When deciding on spending decisions, supermarkets will not consider an innovation that takes too long to pay back the investment; they are often not interested in anything that takes more than three years to recover the cost. The aerofoils pay for themselves much more quickly than that, with McAndrew saying that the payback time can be less than a year.

The idea is certainly popular with the UK's supermarkets. Sainsbury's adoption of the technology was the breakthrough and opened the door to others. Many of the UK's big stores have taken the idea on board, including Asda – which announced in September 2018 that it will fit aerofoils to fridges in 187 of its supermarkets – and Boots. Interest is also growing outside the UK with aerofoils appearing in the US, Europe, Australia, South Africa, and the Middle East.

A GROWING PARTNERSHIP

Large retailers may not feel comfortable dealing with a startup company, McAndrew admits, so having Williams on board helps. "It is F1 technology we are using," he adds.

As McAndrew describes it, working with Williams "is a great partnership", working on new products for example. Now a growing business, Aerofoil Energy licenses underlying patents from Williams but holds the patents for its aerofoils. The fledgling business also benefits from regular input from Williams on strategy and how to take the technology that they developed together out to the rest of the world, which is now a high priority for Aerofoil Energy. With luck, shoppers in other countries will soon see the decline of cold aisles too.

BIOGRAPHIES

Paul McAndrew is Founder and CEO of Aerofoil Energy. He is a display refrigeration specialist with a wealth of experience in the commercial refrigeration sector. Over the past 15 years Paul has launched seven UK startups in the refrigeration and technology sectors and also co-founded a distributed computing platform.

Christian Bedford is Head of Legal at Williams Advanced Engineering and a Director of Williams Technology Ventures. He works across the commercial side of the organisation as well as the legal department and remains focused on helping to drive business growth and direction through technology innovation.

THE EVOLUTION OF EARTH OBSERVATION

A mosaic of cloud-free images captured by the European Space Agency's Copernicus Sentinel-3A satellite in 2017 shows the entire European continent during summer, demonstrating the dryness experienced in regions including Spain, Italy and Turkey © Copernicus Sentinel data (2017), processed by Sinergise/ESA

Satellite images are used to monitor changes in Earth's natural and built environments, with applications in areas as diverse as land use, natural disasters and climate change. Developments in technology are making this data more widely accessible and easier to use. Science writer Tereza Pultarova spoke to companies that are using the data to solve problems on Earth and how artificial intelligence is helping them to do that more quickly.

Earth observation satellites have, after many years in orbit, collected information for environmental monitoring, meteorology and map-making, among many other functions. However, until recently, companies and researchers found it hard to access satellite data. Before the 21st century, a handful of government-funded missions supplied images to defence and government users. Everyone else had to buy satellite data, which was expensive even for rich oil and gas companies. There were so few images available that some satellite data analysts had just one image a year to work from.

Now, however, Earth observation has started to change. The sector has gone from an age of data starvation to an era that could almost be called data overload. In the US, the Landsat programme is the longest-running provider of satellite imagery of Earth, which registered users can access for free. Its first satellite was launched in 1972 and the most recent, Landsat 8, in 2013, with just two of the eight satellites launched as part of the programme still running. During that time, images from Landsat satellites have assisted with natural resource management and environmental disasters, and even helped one researcher discover new species of butterfly and snake in Mozambique.

Meanwhile, in Europe the European Union and the European Space Agency (ESA) collaborated on Copernicus, the multibillion-pound Earth observation programme described as the largest in the world. Consisting of a family of Sentinel satellites that circle the Earth at different altitudes and orbits, Copernicus provides images free to registered users in academia, as well as entrepreneurs looking to develop commercial applications. Copernicus launched the first satellite of the constellation, Sentinel 1A, in 2014 and now flies seven satellites.

The speedy development of electronics, the emergence of smartphones, and ever smaller and cheaper, yet more powerful, computational devices have also led to such instruments as CubeSats. These shoebox-sized, inexpensive satellites can be built and launched within a few months with technology that is sophisticated enough to provide usable observation capabilities in low Earth orbit, such as remote sensing or communications. The boom in development of CubeSats has meant that more than 800 satellites had been launched by April 2018.

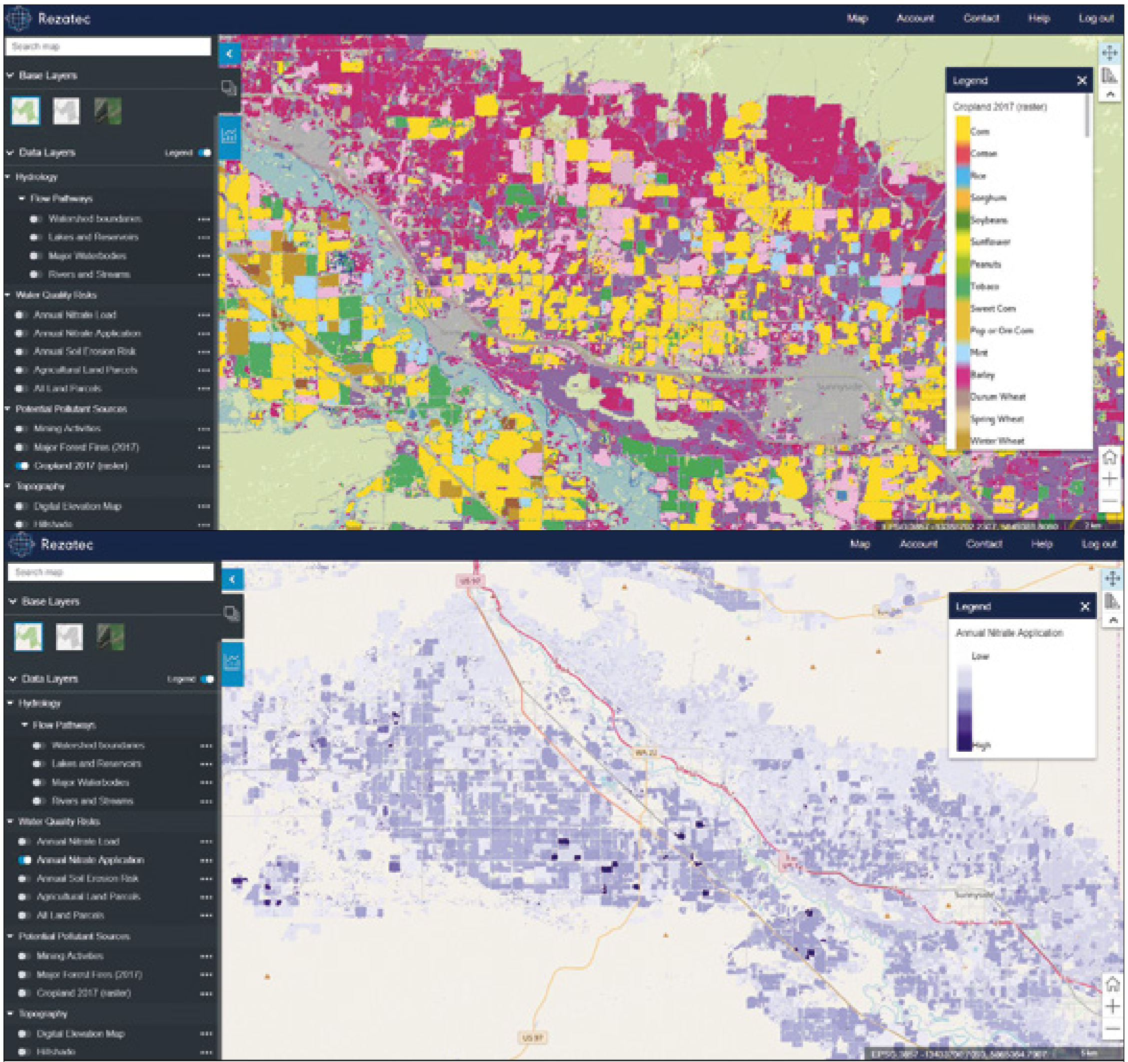
Developments such as Copernicus have led to an exponential increase in the availability of Earth observation imagery. Where previously satellite images were too few and too expensive for analysts to work with, companies looking to take advantage of the view from space can now work with more than 70 free, high-quality, optical images a year, for any location in the world. However, all these companies face the same challenge: how to extract valuable information quickly and reliably from the large amounts of data that pour in from satellites.

ARTIFICIALLY INTELLIGENT ANALYSIS

Whereas in the past a human analyst from an organisation would spend weeks analysing a single image, engineers from third-party companies now train computers to scour the satellite data as it comes in. That data has already sparked off a wave of new applications: frequent images of the same area allow these companies to monitor changes and can provide valuable insights for a wide range of industries, from agriculture and mining to insurance. However, such is the rapid change in the technology that companies providing these services can find it difficult to persuade potential clients that satellite data really can provide useful information and even save costs.

Philip Briscoe, Chief Operating Officer of geospatial data analytics company Rezatec, based at Harwell Campus in Oxfordshire, says that customers' interest increases as soon as they see how easy it is to solve their problems with intelligence derived from satellite images. For example, one of Rezatec's projects was a collaboration with Portsmouth Water, which had witnessed rising nitrate levels in groundwater for some years and wanted to understand more about the sources of this pollution. Removing the contaminants and making the water fit for human consumption needed a complex and costly treatment process, and the water company hoped that discovering the source of the problem would solve the situation much more efficiently.

Portsmouth Water was not only interested in land management related to farming but also that related to equine use, for example horse paddocks and manure heaps, which can



Rezatec's approach helps water utilities identify risk of pollution from agricultural land use. The top image shows the automation of crop identification through the interpretation of satellite data (radar and optical) using machine learning techniques. Engineers feed vast volumes of data into Rezatec's crop ID model to train it to recognise the 'signature' of specific crops with over 97% accuracy. The bottom image shows estimates of nitrate application volume based on crop type and application of fertilisers, which is then fed into the model to map risk to water sources, such as rivers and reservoirs, to support catchment management activity © Rezatec

all produce varying localised sources of nitrate pollution. Rezatec initially used its crop identification and land use algorithms to interpret satellite data to produce an interactive map. Using modelling techniques to analyse the topography and hydrology of the area, the likely overland flow of nutrients and pesticides that impact pollution was mapped, along with overland flow paths and sinkholes that allow nitrate pollution to enter the groundwater.

It knew that the area that Portsmouth Water operates on is situated on chalk land, which meant that it was very easy for surface water to penetrate into groundwater. While there was nitrate from equine activity, the problem was exacerbated by the volume of sinkholes in the ground that were leaching nitrates from agricultural activities: rain was washing away pesticides and fertilisers that farmers were using on crops. Using the satellite data, Rezatec could identify which fields were causing the problem and enable Portsmouth Water to interact with landowners to help protect the water resources.

Building on this, Rezatec extended its services to water utility companies by looking at pipeline leakage risk and how to enable more proactive and efficient asset management. This service begins by feeding various types of data into Rezatec's geospatial analytical engine. This includes weather data, soil maps, satellite data and information about the state of the infrastructure and past incidents provided by the water utility companies. Rezatec then uses machine learning to build an understanding of the conditions under which failures occur. Observations of ground conditions are continually monitored to quantify likelihood of failure across the network. Pipelines at most risk of leakage are highlighted for proactive monitoring and then Internet of Things sensor activity can be fed into the service to pinpoint issues early.

Briscoe says that its pipeline leakage risk service enables water utilities to use their manpower more efficiently and reduce capital expenditure costs such as acoustic loggers; instead of sending ground crews to investigate the entire network at regular intervals, the engineers only go and visit those locations or install loggers where there is a high risk of leakage identified by the system.

Another company based at Harwell Space Cluster dealing with satellite data also discovered that a once sceptical target industry quickly changed its mind about Earth observation data. In 2014, Imperial College London graduate Gareth Morgan founded Terrabotics, which uses powerful algorithms that transform Earth observation data into practical 3D maps for industries in the natural resources sector. In 2011, while the company was still in development, Morgan and his colleagues started approaching oil and gas companies to offer their algorithms.

As more satellites were being launched and large quantities of data started coming in daily, the oil companies realised that they could use satellite imagery not only for slow-moving tasks such as pipeline planning, but also for near real-time monitoring of activities at their own, as well as competitors', sites.

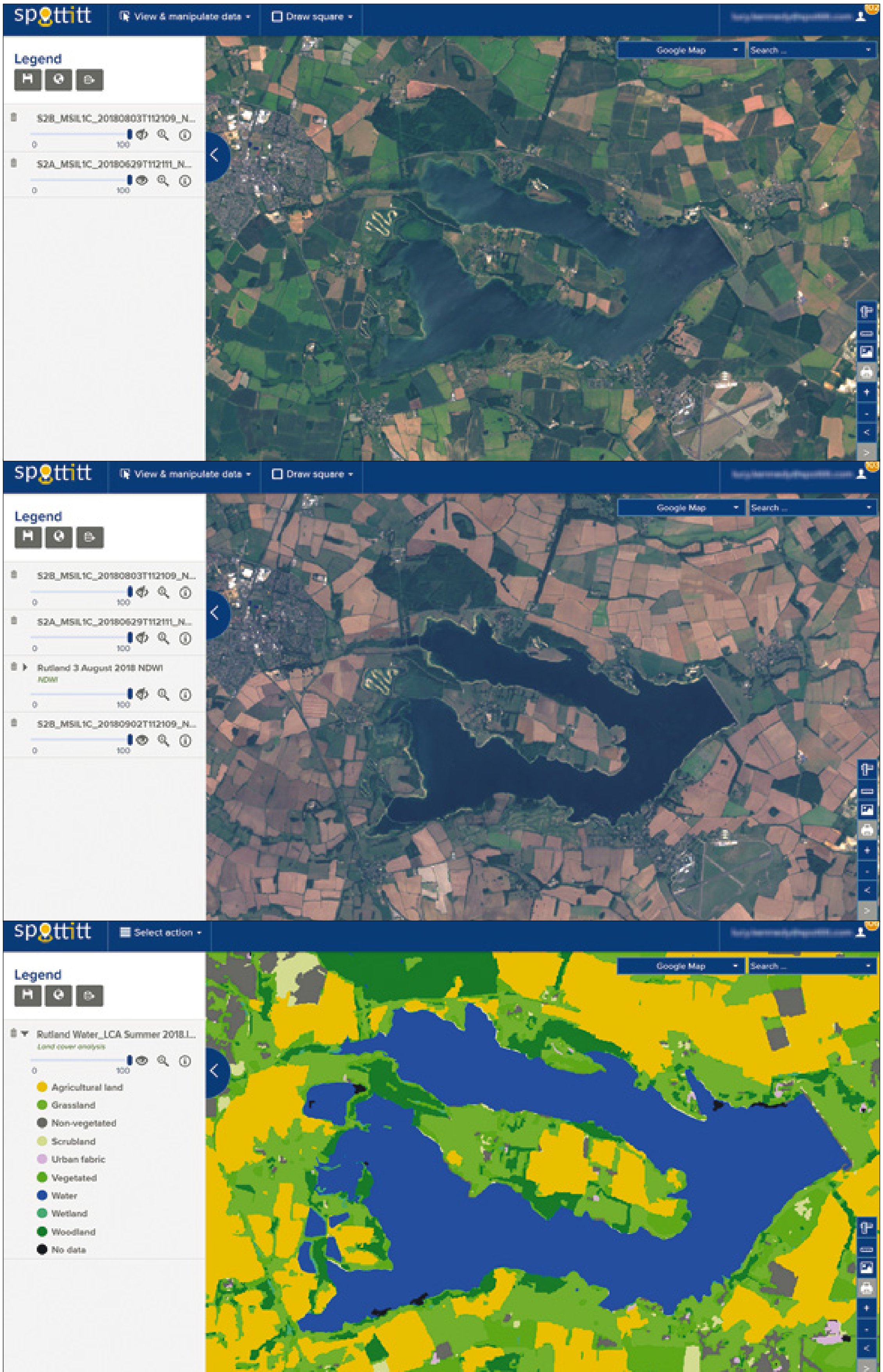
Terrabotics artificial intelligence algorithms identify and determine changes in the images – a process that is similar to facial recognition but applied to infrastructure. For example, every five days the company counts new oil-drilling sites, new pipelines and new roads, and supplies the data to oil companies and economists.

One of the areas that Terrabotics monitors is the US state of Texas – one of the most active oil-drilling regions in the world. It was here that the algorithms assessing the satellite data spotted a new pipeline being built over the land of a company that Terrabotics supplies data to, but it was another company building very close to or over its land. Previously, it would have taken the company several weeks to discover the building work but Terrabotics' algorithms helped them address the problem promptly.

TRAINING ALGORITHMS

However, ensuring that the algorithms are reliable is still a major challenge and requires human input to become reliable. They require a huge amount of data and, to start with, human analysts must analyse hundreds of images and label the objects for the algorithm to identify – a task that can need many people at a time.

There are several different approaches that can be used when developing, training and validating an algorithm, but they all require a mix of expertise, trial and error, frustration, and perseverance. This is according



Images from the ESA's Copernicus Sentinel satellite show the area around Rutland Water in the UK. The top image was taken in June 2018, while the one in the middle was captured in September 2018, demonstrating how the hot summer dried out surrounding fields and water levels in the reservoir dropped. The image at the bottom shows an automated land cover analysis of the same area © Produced from ESA remote sensing data, image processed by Spottitt Ltd

to William Ray, Earth Observation Specialist at Spottitt, another Harwell Campus-based startup that provides a range of fully automated analyses based on satellite imagery to the energy, environment and infrastructure sectors. It helps the renewable energy sector find sites with suitable geography for development of new power generation installations anywhere in the world, saving them time and money. Ray says that the challenges of automating complex work processes are significant, involving numerous image pre-processing, algorithm processing and post-processing steps on gigabytes of data, coupled with the complexities of ensuring solid algorithm performance across multiple sources of satellite imagery from across the globe. However, advances in cloud computing, increased image availability and AI techniques have allowed the company to train and validate its various algorithms to help customers understand key factors such as land cover and the location of obstacles such as water and buildings.

According to David Petit, Head of Earth Observation Applications at space systems company Deimos Space UK, the challenges do not end with a working algorithm. Data needs to be presented in the right way for the algorithm to produce accurate results. For example, effects of the atmosphere, such as cloud cover, need to be filtered out. Companies also need to make sure that the location is correct, as some satellites are better than others at knowing exactly where an image was taken.

An algorithm could, for example, misinterpret the fact that two images were taken at different times of the day and attribute the difference in illumination to a change in the scene. Before running its AI algorithms, Deimos puts the incoming data through an intelligent platform, called Service4EO, which corrects and organises the data in an AI-friendly way. The platform gathers inputs from different satellites and other sensors, such as drones and ground sensors, about the areas of interest, for example fields for farmers and agronomists. Service4EO identifies suitable images, clears them of noise and structures them in a coherent way for the AI algorithm to analyse, so that the customer gets the information they need without requiring any special training.

When it comes to training AI, a traditional approach has been about increasing the amount of data used to train the algorithms. However, Gareth Morgan from Terrabotics believes that quality instead of quantity provides better results. By properly refining the original datasets that have trained the AI algorithm, Terrabotics can reduce the amount of training data that needs to be fed into the computer to make the algorithm work reliably.

The company's key innovation is presenting AI algorithms that perform the eventual analysis data in 3D. Dedicated algorithms automatically transform two or more overlapping images of a scene taken at different angles into a 3D representation. Instead of two cameras imaging a scene at a set distance, the input for the satellite 3D image is usually taken from the same satellite. The company feeds these 3D reconstructions into the algorithm together with the flat 2D images.

The algorithm Terrabotics has developed can extract further information from the 3D images that is useful to customers. It precisely matches pixels between each image, which calculates the 3D shape and heights of the terrain via triangulation. This way, the technology can measure the differences between the different images right down to the 'sub-pixel' level.

THE FUTURE OF EARTH OBSERVATION

Undoubtedly, developments in technology, such as CubeSats and AI, have transformed how satellite data is being used to solve challenges on Earth, and the number and accessibility of images is only going to increase. In October 2018, the UK government announced that its Space for Smarter Government Programme will provide government departments, emergency services and local authorities with free access to satellite data images. Public-sector organisations are already carrying out pilot projects: Bournemouth Borough Council is using machine learning to identify the best locations for electric vehicle charge points in the city, and the Environment Agency is looking at using satellite images to monitor plastic pollution around Britain's coast to support clean-up operations and protect wildlife.

While Earth observation draws on many different technologies and areas of expertise, it seems that AI is a key factor in utilising the data, allowing users to quickly analyse and monitor satellite images. As the development of basic AI algorithms progresses, companies developing Earth observation data solutions hope that their work will eventually become easier. Self-learning algorithms and algorithms mimicking the human ability to use memory could further reduce the amount of work needed to train algorithms and the continuing advancements of computational technology will make everything run more smoothly.

While there have been several attempts in the past to commercialise Earth observation data, the current one finally appears set to succeed.

BIOGRAPHIES

Philip Briscoe is Chief Operating Officer at Rezatec, responsible for the company's go-to-market strategy, international expansion and partner relationships. He has over 20 years' experience in the technology industry, holding senior management positions across a diverse range of software companies.

David Petit leads the Earth Observation Applications Team at Deimos Space UK, developing the use of artificial intelligence in projects for the European and UK space agencies. He has a PhD in computer sciences, applied to radar imagery.

William Ray has been Spottitt's Earth Observation Specialist for two years. He graduated from Aberystwyth University with a master's in Earth observation and geography and has more than five years' experience in the geospatial industry.

AN EASIER WAY TO DIAGNOSE DISEASE

Owlstone Medical has created the first technology capable of capturing and analysing breath samples in a robust and reproducible way, so that it can be used in large-scale clinical trials. Breath testing for diseases could aid earlier diagnosis, leading to improved patient outcomes and reduced treatment costs
© Owlstone Medical

A breathalyser that can save lives and money won the 2018 MacRobert Award. Breath Biopsy®, the chemical analysis of volatile compounds in exhaled breath, lies behind this innovative approach to medical diagnosis. Science writer Michael Kenward OBE learned about the clever engineering behind the technology and how it is being used to collect and analyse breath samples on a wider scale.

The underlying idea behind Owlstone Medical's innovative breakthrough in medical diagnostics is, in the words of Billy Boyle, its CEO and co-founder, that "every chemical has its own smell 'fingerprint'". At first, Boyle and his colleagues at the University of Cambridge established Owlstone Inc to create chemical sensors for military systems. Medical diagnostics came later. In 2004, the researchers set up the company to commercialise their academic work in micro- and nano-engineering, developing small and inexpensive sensors on silicon chips. Their ambition was to swap expensive sensors and systems in devices that cost around £10,000 for sensors that cost a few pounds.

Owlstone's aim was always to protect the public. The idea was that it could play a role "protecting every train, financial institution, government building, airport, stadium and indeed any target at risk from chemical or explosive attack". Owlstone's sensors could detect some 20 different chemical 'fingerprints', which meant that it could check simultaneously for sarin and mustard gas, for example.

Owlstone Inc went on to build a successful, and now profitable, business in chemical sensing for customers in defence, security and business. Over the past decade, the company has raised $38 million in investment and won defence contracts worth more than $32 million. The engineering promise of that early progress was such that Owlstone was one of the three engineering innovations shortlisted for the MacRobert Award in 2008.

A family tragedy accelerated Owlstone's move into medical diagnostics. Boyle's wife died of colon cancer because of a late diagnosis, and Boyle admits that anger spurred him on after his wife's death. "Anger is an energy: it is what drives me and my team," he confesses. He started working with medical experts to devise ways of diagnosing cancers earlier as: "early detection is our greatest opportunity". Another important benefit of Breath Biopsy is its patient-friendly nature. "Breath is the ultimate non-invasive test," says Boyle.

From the outset, Owlstone's 'manifesto' had included medical applications, but that was a far more challenging goal, not least because despite a long history as a possible diagnostic technique, the medical world had yet to accept the idea of 'breath diagnosis'. Boyle decided to do something about it. The argument is straightforward: metabolic processes in the body create a very large array of different chemicals depending on what is going on. These complex chemicals enter the bloodstream then flow around the body, hence entering the lungs, which act as an oxygen exchanger for the blood. "Your lungs are very good at exchanging gas from blood to the airways," says Boyle. "Every time you breathe out there are thousands of volatile organic compounds (VOCs) in your breath." Underlying changes in metabolic activity can produce patterns of VOCs that are characteristic of specific diseases.

While Owlstone's founders always thought that their sensors might play a role in medical diagnosis, they had to work out how to do it. Perhaps even more importantly, they also had to prove not just that their approach made medical sense but persuade the medical community that it would work. In essence, Owlstone had to devise a new form of medical diagnostics based on chemical analysis of the VOCs in breath.

BREATH BREAKTHROUGHS

Over the years, there have been many newspaper reports of 'breaththroughs' in the development of an electronic nose, but they rarely go further than the headlines. One review article summed

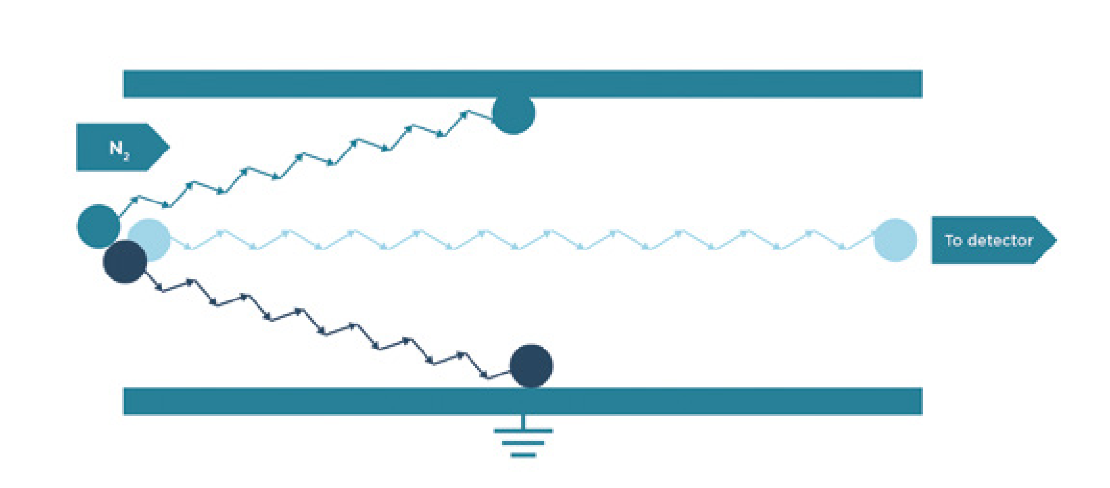


Figure illustrating how field asymmetric ion mobility spectrometry (FAIMS) works. The diagram shows three ions, all demonstrating different mobility behaviours under the influence of the electric field. The paths of two ions collide with walls, but the third ion has the appropriate DC voltage applied, meaning it traverses the device that scans these DC voltages, producing a compensation field spectrum for the transmission of all ions © Owlstone Medical

up the situation not long after Owlstone opened for business: "Despite the success in some areas, the efforts to arrive at a universal device that can make fine discrimination of flavours, perfumes, and smells and eventually replace the human nose are disappointing."

By the time Owlstone turned its attentions to medicine, it had overcome some of that disappointment. But medical diagnostics is a very different market to sampling air to find harmful chemicals. Medical systems require long and expensive trials to take new technology through the regulatory processes that are essential for diagnostic systems.

It was only in 2016, more than a decade after it opened for business, that Owlstone's founders set up a new medically oriented company, Owlstone Medical. The idea that you could use breath sampling to diagnose diseases has been around for some time – Hippocrates (460 to 370 BC) first linked breath odour to underlying diseases – but it got nowhere: as well as small and inconsistent studies, the most significant issue was a lack of a standardised technology for collecting high-quality breath samples and analysing them reproducibly. Before Owlstone could tackle that challenge, it had to adapt its existing sensors and create an optimised device that could take a sample containing VOCs and give a reliable analysis of what was in a breath sample.

The platform includes a patented chemical sensor on a silicon chip, based on a technique called field asymmetric ion mobility spectrometry (FAIMS). Owlstone's technology revolutionised ion mobility spectrometry by turning to micro- and nano-fabrication to miniaturise the spectrometer and its channels, while integrating tiny detectors into the device along with a solid-state FAIMS filter. The result is a programmable sensor on a silicon chip. Tweaking the software can program the chip to instantly detect different chemicals. FAIMS is a variant of ion mobility spectrometry, where a tiny radioactive source ionises the VOCs in a breath sample. By applying an alternating electric field across the path of the ions, the chip can act as a filter that allows only certain ions through to the sensor.

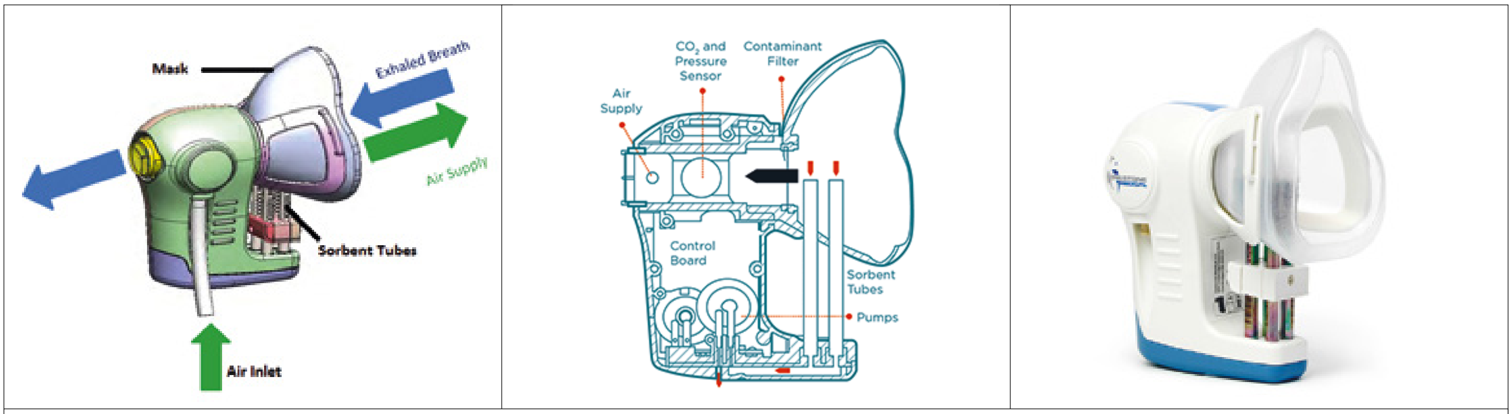
The ionised VOC gas passes through channels under the influence of an asymmetric radio frequency field [see figure above]. Under the first portion of the waveform, ions will drift in one direction at a speed based on their individual mobility in that electric field. As the field polarity is reversed, the ions change direction and speed based on the new field conditions. As the mobility of the ions during the two parts of the waveform is rarely equal, there is usually a net drift towards one of the electrodes. In FAIMS, this net drift is corrected by applying an additional DC voltage, known as the compensation field, focusing specific ions through the device to the detector. The device scans the DC voltages to produce a spectrum that reveals the VOCs that are present in the sample.

TAKING A SAMPLE

The sensors and measurement system on their own are of little value without a reliable and reproducible way of capturing the VOCs in breath. Owlstone developed its ReCIVA® Breath Sampler device, one of the innovations for which it won the MacRobert Award, to fill this role and to create a standardised breath sampling and analysis procedure. Subjects breathe a controlled supply of air, and samples of their exhaled breath are captured on Breath Biopsy cartridges, which can then be analysed to determine their VOC profile.

When developing the breath sampler, Owlstone had to pay careful attention to the cost of the cartridge that captures the VOCs, as disposable cartridges would have been too expensive. The solution was to devise cartridges that can be reconditioned and sent out to be reused.

The design for the ReCIVA Breath Sampler drew on discussions with more than 100 multidisciplinary experts in breath



The ReCIVA Breath Sampler monitors patient breathing and automatically selects a fraction of expired breath to be captured. Breath is directed into four collection tubes, which are packed with different sorbents that are optimised to collect volatile organic compounds in breath © Owlstone Medical

diagnostics. The result is a breath sampler that is becoming the industry standard for the reliable and consistent collection of breath samples. The standardised device for breath sample collection was essential if breath analysis was to be effectively deployed in clinical trials. As Owlstone describes it: "this also means that we now have technology that is robust enough to collect reliable breath samples in clinic, and identify biomarkers for disease in breath". A key feature is the reduction in the variability of the measurements, allowing statistically predictable decisions to be made about response to treatment.

The device consists of a base unit that can be attached to a PC or tablet to control and monitor the sampler. The ReCIVA also has a positive pressure air compressor for patients who need it as well as a disposable mask with a built-in bacterial filter to prevent contamination of the base unit and a cartridge for collecting the sample. Owlstone's goal is to measure traces of VOCs in a quantifiable manner from precisely sampled breaths. A critical feature is the ability to reduce sources of potential contamination in the whole collection cycle.

The ReCIVA base unit monitors the patient's breathing by checking the pressure and by measuring CO_2. It automatically selects which section of the expired breath to capture. It then controls piezoelectric valves to direct the breath sample into one of the four collection tubes that form the Breath Biopsy cartridge.

SHARED EXPERTISE

The technology was just the beginning of Owlstone's challenge. It also had to persuade medics that Breath Biopsy made sense, which meant working with doctors to understand which VOCs could act as biomarkers for specific diseases. The company did not have to start from square one when it set out to make the case for its Breath Biopsy platform. There is a sizeable body of literature on the medical use of VOCs, including a dedicated *Journal of Breath Research*. Plenty of papers describe research into the use of VOCs, some of them based on Owlstone's technology, but the concept had never made it into regular medical practice.

Owlstone is helping to change that. The current research activity in the area is one indicator that medical researchers take the idea seriously. As well as clinical trials, over 100 clinical sites across the world use Owlstone Medical's Breath Biopsy technology. Pharmaceutical companies, clinical research departments in hospitals, academic researchers and other commercial organisations have taken up the idea for their own research in clinical trials and precision medicine applications.

One example of the take up of the diagnostic platform is GSK, which recently chose to integrate it into the clinical development programme of one of the novel drug candidates in its respiratory disease pipeline, to assess whether the right treatment for the right patient can be identified. AstraZeneca is also using Breath Biopsy to identify novel biomarkers for personalised medicine applications in asthma and chronic obstructive pulmonary disease. Another sign of the company's efforts to spread the word was the recent *Breath Biopsy Conference 2018*, which it described as 'Owlstone Medical's inaugural community meeting for breath researchers'.

The final piece of the jigsaw was to develop a way to turn Owlstone's engineering into a profitable model. The company does not just sell breath samplers and FAIMS instruments. In early 2017, Owlstone Medical launched its Breath Biopsy Services, so that academics, clinicians and pharmaceutical companies can explore breath-based diagnostics.

Researchers who want to implement Breath Biopsy have various options. They can lease the ReCIVA Breath Sampler and buy biopsy kits to collect breath samples. When it comes to analysing samples, users can either send them to Owlstone's

Owlstone hosts 'the world's largest Breath Biopsy digital biobank', which is a valuable resource available to researchers using its Breath Biopsy Services © Owlstone Medical

labs or they can conduct onsite analysis with the Lonestar® VOC Analyzer.

One outcome of Owlstone's analysis service has been 'the world's largest Breath Biopsy digital biobank' that relates VOCs on breath to particular diseases. This resource is available to researchers who send samples for analysis and want to explore biomarker classifiers and gain valuable insights into how they might perform in larger patient populations. The biobank includes thousands of breath VOC profiles matched to phenotype. As Owlstone collects and analyses all VOCs on breath, each sample becomes a snapshot of the health of an individual at a moment in time. In this way, it enables studies performed by Owlstone, or on behalf of clients, to be augmented with in silico patient breath samples, and offers the potential to test hypotheses in the biobank without the need for additional patient samples. It is helping to overcome some of the historical challenges associated with identifying VOCs and relating how these are linked with specific diseases.

The benefit of the digital biobank and Breath Biopsy can go beyond disease diagnosis. There is growing interest in the idea that genetics can affect patients' responses to different therapies. Owlstone believes that Breath Biopsy could help to identify patients most likely to respond to a particular therapy. Not only would this deliver better outcomes for patients, it could also reduce the costs of treatment, for example by reserving the use of expensive drugs for patients who are more likely to respond. Professor Sir Saeed Zahedi OBE RDI FREng, one of the MacRobert Award judges and Technical Director of Blatchford, explained: "With $400 billion a year wasted on ineffective drugs, there is a global move towards precision medicine – ensuring that the right intervention and drug are given to the right patient at the right time."

GLOBAL GROWTH

With so much going on in its Breath Biopsy platform, Owlstone has naturally worked hard to protect its intellectual property rights with, at the last count, nearly 40 patents. The company has set itself ambitious targets. It aims to save 100,000 lives and $1.5 billion in healthcare costs.

Development on this scale takes money, not least because it involves taking a whole system approach that takes in health economics as well as the development of the technology and supporting services. With a team of just over 150 people in Cambridge and plans to set up operations in the US and other countries, the company has been seeking investors. Not long after Owlstone Medical collected the MacRobert Award, it finalised another round of fundraising, with $50 million raised. The company has raised around $73 million since its creation in 2016.

The funding round also attracted investors from promising markets for Breath Biopsy, including China. Boyle said: "We enjoyed particularly strong interest from Asian investors in the round, and as China is a key market for the company, we are encouraged by the strategic value of these partners as we seek to accelerate entry into this market." The new funding will also support the creation of a new analytical laboratory in the US.

Professor Sir Saeed Zahedi certainly sees plenty of promise in this new approach to medical diagnosis. "The future road map of this innovation in medical device technology is transformative and could be the key for future self-diagnostics as part of a long-life care revolution."

OWLSTONE IN NUMBERS

- More than 100 breath diagnostics experts support development of the ReCIVA Breath Sampler.
- $73 million in total funding raised since 2016.
- Up to 4,000 patients in NHS-supported LuCID lung cancer trial.
- ReCIVA units deployed in more than 100 sites.
- The Breath Biopsy platform aims to save 100,000 lives and $1.5 billion in healthcare costs.

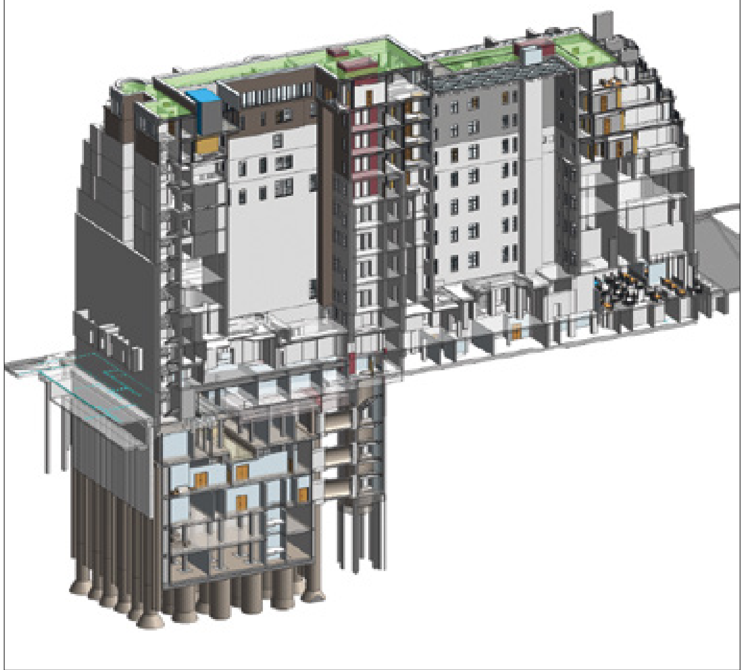
BIOGRAPHY

Billy Boyle is an engineering graduate from the University of Cambridge. He is one of the original co-founders of Owlstone Inc, spun out of Cambridge in 2004. In 2016, Billy led the process to spin-out Owlstone Medical Ltd and became the founding CEO.

GOING UNDERGROUND

Engineers are completing a new five-storey basement underneath London's Claridge's, with no interruption to the hotel overhead. This extraordinary achievement has been made possible by a combination of traditional mining techniques and state-of-the-art structural and geotechnical engineering. Hugh Ferguson talked to engineers from McGee and Arup about the project, believed to be a world first for concurrent underground development and occupancy on such a scale.

Claridge's hotel in Mayfair dates back to the 1890s in its current form. However, the building needed more space for its five-star facilities, including a spa and a swimming pool. With planning regulations removing the possibility of building upwards, a five-floor basement has been dug out below
© Stockphoto/IR_Stone



A cross-section through the front of the hotel shows the new basement below the art deco extension that was added in the 1920s © Arup

Claridge's hotel in Mayfair, once described as the 'first hotel in London' and later as 'an annexe to Buckingham Palace' because of its strong royal connections, opened in 1856 as an amalgamation of five terraced buildings. In the 1890s, it was built and redesigned in its current form, and a large extension, encompassing 80 new rooms and a ballroom, was added on the east side in the 1920s. However, in order to thrive as a top five-star hotel in the 21st century, the hotel needed more rooms and more facilities, including a spa and a swimming pool. For planning reasons, building upwards was out of the question, so extending downwards became the preferred solution. The real challenge came from the need to keep the hotel open and fully functioning throughout the building works: a temporary closure would risk regular visitors changing their loyalties before the hotel reopened.

In 2015, the Maybourne Hotel Group asked engineering firm McGee to create a five-storey basement beneath the art deco extension. McGee was the only contractor to believe that the work was possible without closing the hotel [see *A family affair*], but realised that help was needed to confirm that it could be done without endangering the building overhead, so Arup was brought on board as geotechnical and structural engineering consultant.

STABILISING THE BUILDING

The 1920s eight-storey extension is supported by 61 steel columns resting on a 1.1-metre-thick, 50 metre by 25 metre reinforced concrete raft (a slab spread out under the entire building) directly below the lower ground floor, with no pile foundations beneath. Some distance beneath the raft was firm London Clay, but unfortunately in between the raft and the clay were treacherous, uneven layers of gravel, up to half a metre thick, overlain by saturated silt with a high water content up to two metres thick, which was an alluvial flood plain feature of the former course of the River Tyburn. In its contained state, this silt had a high bearing capacity and could satisfactorily support the building overhead. However, once disturbed, below the water table the material flowed like 'running sand', or where it was a clayey silt, it behaved like toothpaste. Either way, both would damage the existing raft if a novel solution could not be found to address this ground risk.

Arup and McGee came up with a plan to create the new basement:

A FAMILY AFFAIR

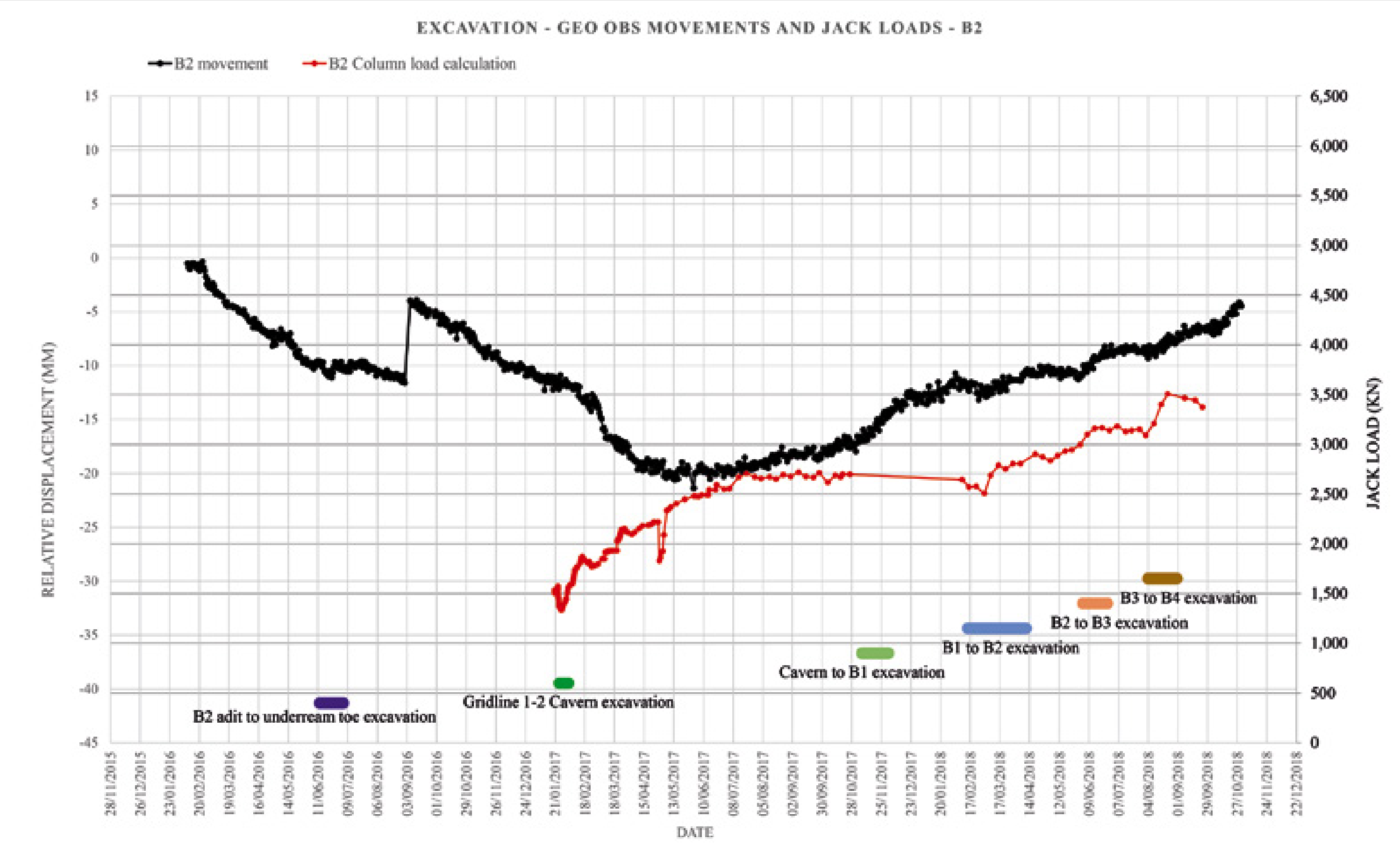
In 2007, Wembley-based McGee was invited, along with several other civil engineering contractors, to submit a proposal to extend the basement beneath Claridge's by two storeys. Managing Director Jim Mackey devised and proposed a scheme that would keep the hotel open throughout: all the other contractors required the hotel to close during the works.

But the 2008 recession and disputes over the hotel's ownership intervened and the scheme went into cold storage. Meanwhile, Jim retired in 2015 and resettled with his wife in Ireland.

A few weeks later he was sitting at home when the phone rang. It was Claridge's. The project was once again live, only now the hotel required five storeys instead of two: "We want you to do it, and it starts next week." Jim returned to London, initially just to start the project up, but he got too involved and has stayed throughout, enlisting the help of his daughter as senior engineer.

Michelle Mackey had not intended to follow her father into construction. After graduating in mathematics from the University of Southampton and gaining a master's in statistics the following year, she took a job in research. But she found that she was getting bored. It was only then that Jim suggested engineering, and she enrolled at London South Bank University to complete a civil engineering course part time.

The two make an effective team, with complementary skills and experience. With the Claridge's basement complete, will Jim now return to retirement? It seems there may be just one more project for the pair to work on together.



Measurements of loading (red line – from January 2017 when loading was transferred to the new columns) and displacement (black line) at the top of one of the 61 new columns at the base of the existing building, during construction works up to September 2018. The various construction activities are indicated beneath. The graph shows that, during top-down construction (B1 to B4 excavation), heave forces acting on the underside of the caisson foundation have been pushing this column upwards since October 2017 (black line), with a corresponding increase in the load in the jack, from what the engineers consider to be heave pressure © Arup

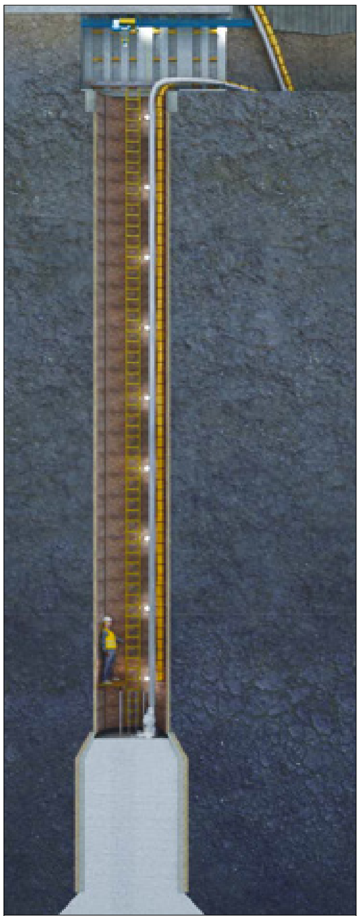
- Stabilise the silt, then carefully excavate a series of strongly supported tunnels directly underneath the raft, with a group of horizontal passages running from the tunnels to provide access to the points directly beneath each of the building's columns.
- Hand-dig 61 caissons (large, watertight retaining structures), up to 30 metres deep, below the raft.
- Fill the bottom of each caisson with concrete to form new piles up to the underside of the new basement.
- Construct reinforced concrete columns within the caissons, up from the top of the piles to the bottom of the raft.
- Transfer the load from the existing building onto the new columns, so relieving the loads on the raft.
- Gradually excavate downwards through the clay to create the basement levels, casting new walls and floors on the way.

As if this was not challenging enough, the work had to be done with no noise or disturbance to the occupants overhead. The team was initially allocated just one small room on the lower ground floor (with a second room and a connecting corridor added later). All excavated material had to be removed, and all material and equipment brought in, through one window at the rear of the building, and lifted with a single hoist through one small hole in the raft. There was virtually no storage space, so all deliveries and removals had to be carefully planned on a 'just in time' basis. No noise, vibration or other disturbance to the hotel above could be tolerated. With a 'live' building overhead, the safety and stability of the structure at every stage was critical.

The first two challenges were to gain an understanding of the existing concrete raft and how it would behave at every stage of construction until its eventual – very different – role as a suspended slab, and to find a way to deal with the saturated silt immediately below the raft.

A two metre by two metre hole was cut through the raft, both to provide initial access and to enable samples of the concrete to be analysed and tested. The hole was later doubled in size to provide the main access route for materials.

With the raft, the concern was not so much whether it would sink or even tilt during the work, but whether it would bend and crack, and if so, where and how. Tests on the sample confirmed that the concrete was good quality. Desk studies



One of the 61 hand-dug caissons with a temporary steel lining, widened out below the bottom of the new basement where it was backfilled with concrete to form a new pile © McGee

A miner hand excavates one of the 61 steel-lined caissons (left), while another places a reinforcing bar for a new column within the tight space of a hand-dug caisson (right) © McGee

from the time of the extension's construction unearthed reports that 75 tonnes of steel had been used in the raft – slightly more than the relatively light reinforcement found in the sample would suggest. The probable explanation was that 'additional' reinforcing steel is located beneath the columns.

Given the uncertainties, the engineers' approach was to adopt several different methods of analysis producing different results, enabling sensible judgements to be made about the loads and deflections that the concrete raft could safely withstand. As a 'worst case scenario', it was assumed that the concrete could develop potentially large cracks in areas of high flexural stress and low (or no) reinforcement. Punching shear – often a governing design criterion in modern raft design, which is the tendency of the column with its large point load to 'punch' a hole through the raft – was less of an issue because of the ability of the existing grillages (an arrangement of metal beams to create large steel feet) at the base of each column to spread the concentrated column loads. The main strength analysis methods adopted were Johansen yield line analysis and an arching model, which took advantage of the non-simultaneous excavations to develop thrusts through the surrounding raft. Engineers assessed deflections using tools ranging from simple geometrical models of strain (taking into account the high ductility found through testing the mild steel rebars) through to sophisticated 3D finite element cracked concrete time-history analysis. The edges of the slab were a particular concern, including the effects of load redistribution in the existing masonry walls.

Overall, the analysis gave confidence that loading at every stage could be kept within the acceptable ultimate loads – provided that deflections due to excavation were controlled and could be measured – and that the chosen approach was feasible and safe.

A 3D finite element geotechnical model of the raft's interaction with the ground was subjected to different excavation activities (tunnel excavation, shaft caisson construction, removal of temporary steel, and soil removal beneath the raft) to predict possible raft movements. This was vital to informing structural models and analysis. This was a project where the structural and geotechnical engineers relied on an integrated approach to design to provide a unique solution.

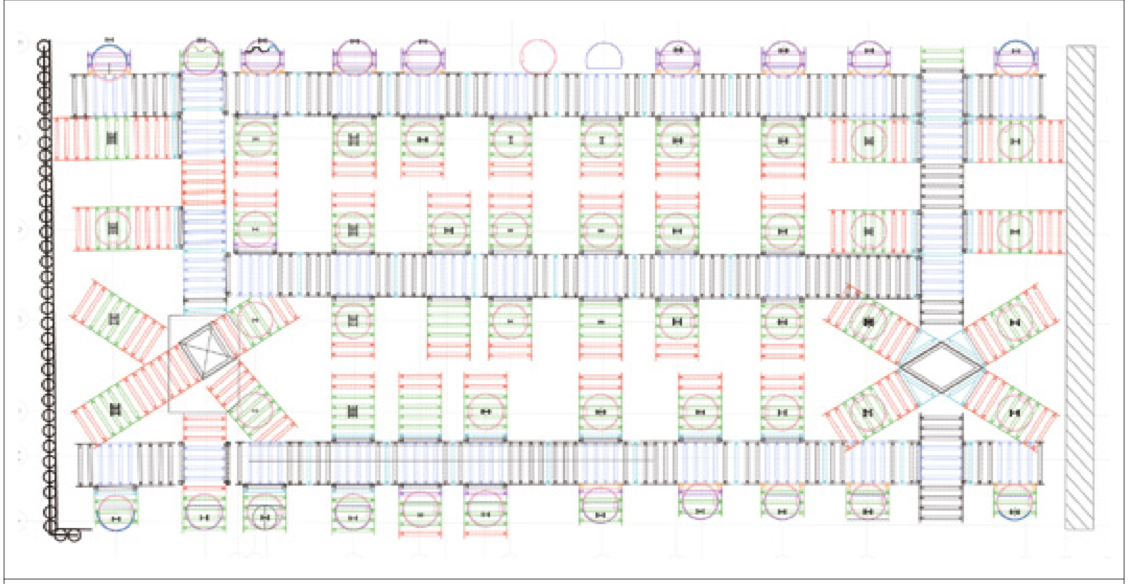
QUIET EXCAVATION

Several methods of dealing with the silt were considered. Grout injection, which is usually used to fill accessible pores between the solid particles in a soil to strengthen it, was not suitable because the material was too dense and clay-like to inject. Ground freezing to stabilise the saturated silt was also rejected because it would have required access to occupied hotel rooms, meaning that the hotel would need to be closed and was therefore outside the client brief. Tests showed that the silt, once dried, formed a remarkably stable clay-like material, so engineers decided to drain the silt using vacuum pumps from several bored wells. First, the perimeter of the site had to be sealed on all four sides to stop more water flowing in. The most challenging part was the north side along the front of the hotel, where no external construction work could be permitted. The solution was a 'water cut-off beam' beneath the edge of the raft, 1.2 metres wide by 1.8 metres deep (to connect into the impermeable clay below) and 25 metres long, created by digging a tunnel using vacuum draining along the edge of the raft, and then filling with reinforced self-compacting concrete.

Now excavation beneath the raft could begin – but very carefully to ensure that only small areas of the raft were left unsupported at any time. Miners dug the first tunnel of 1.8 metres by 1.8 metres in section with stiff steel frames every 500 millimetres to transfer the load from the raft above to the ground beneath. Passages were then excavated out from the tunnel to reach the points directly beneath the hotel's columns, from where the caissons would be sunk.

Two miners used pneumatic spades to hand-dig each circular caisson through the dried silt and clay, installing a temporary lining formed of one-metre-deep bolted steel segments as they progressed. The diameter of the caissons was a critical decision: miners needed sufficient space to work and, at a later stage, to install the formwork and reinforcing steel for the new concrete columns, working in the cramped annular space between the columns and the caisson walls. However, the span of the raft that could be opened up to form the top of the caisson had to be kept to a minimum. A 'sweet spot' of 1.8 metres diameter was eventually chosen.

When the miners reached the bottom of the new basement 22 metres beneath the raft, the diameter was increased to 2.7 metres and more conventional, permanent precast concrete linings of up to four to six metres in depth were installed for the next section. Finally, the bottom of the excavation was 'belled out' to a diameter of up to 4.6 metres to form a broad, flat base for the new piles. The level of the bottom of each pile was carefully chosen to avoid going below the impermeable London Clay, which would have allowed groundwater to enter and required compressed air working. Reinforcing steel was placed and the caissons were then concreted to form solid



A diagram shows the three main tunnels (in blue) – named Tom, Dick and Harry – beneath the concrete raft, with numerous access tunnels to connect to the heads of each of the 61 caissons © McGee

A HOTEL FLOATING ON HYDRAULIC FLUID

Key to the safe construction of Claridge's new basement was the close monitoring of loads and deflections of the existing hotel at every stage of the work, together with the ability to make adjustments to the load distribution if the measurements approached a critical level.

Engineers primarily measured deflections through a real-time monitoring system that was established by installing automatic liquid levelling sensors on each of the 61 columns of the 1920s building, just above the raft, which could tell within one millimetre the vertical position of each column. Sinking of the whole building or upwards heave during construction, even quite substantial movement, or tilting of the slab were of little concern: much more serious was differential movement between the various columns, implying curvature and bending in the raft that could cause cracking.

The initial concern was the effect of draining the silt immediately under the slab, but at every subsequent stage there was potential for differential movement, particularly as the sequencing of the work meant that construction was not progressing evenly across the whole site.

The early works saw less movement than had been expected, and no damage to the building overhead. In particular, the sinking of the caissons caused little movement as the temporary tunnel frames provided support against the underside of the raft and the caisson rings were grouted in place to minimise ground loss.

As each new column was completed, two 800 tonne hydraulic jacks were installed at the top to connect with the raft and existing columns above, which provided the ability to adjust loading and height on each column as required. Two jacks were required because the maximum travel was only 28 millimetres per jack, and it was expected that larger movements up or down would need to be made. Activating the jacks had the effect, not so much of pushing the hotel upwards, but of pushing the columns and piles downwards and absorbing the initial elastic settlement. Engineers measured loading simply by reading the hydraulic pressure in the jacks. Movement or changes in load did not happen suddenly, so there was time to monitor trends, check them against trigger limits set by the design, and plan any remedial action. At various stages of basement construction, excavation caused the ground below to heave, and load had to be removed from some of the jacks to maintain stability.

The jacks are still in place and active, and will be until all possibility of unacceptable movement has passed. In the meantime, the whole art deco extension on the east side of Claridge's remains floating on hydraulic fluid.

piles, up as far as the bottom of the new basement.

Working upwards from here, formwork and reinforcing steel were installed and the concrete poured for the 600-millimetre diameter permanent columns, founded on the new piles and running up the centre of the caissons. At the top of each new column, engineers installed twin 800-tonne hydraulic jacks and used them to start transferring the load from the existing building into the new foundations. The jacks, together with associated measuring equipment, were used to monitor loads and movement, and to make adjustments when necessary [see *A hotel floating on hydraulic fluid*].

The first six caissons and columns were treated as 'trials' to prove the feasibility of the proposed method, and only after their successful completion did the project turn into a full-blown contract. Tunnelling beneath the raft was extended, with three main tunnels – named Tom, Dick and Harry after the tunnels in *The Great Escape* – running most of the length of the raft, and with passageways connecting to the heads of all 61 caissons. There were so many tunnels and so much activity that it reminded those on site of an *Indiana Jones* movie.

With all 61 columns complete, the jacks were operated to transfer an additional load into the columns, equivalent to about three quarters of the dead load of the building. With the building's load now removed from the raft, the network of tunnels and passageways could be removed and excavation of the basement could commence, dismantling the temporary steel caisson rings and adding new concrete walls and a basement slab linked into the new columns. The first basement was completed in February 2018.

In February 2017, Claridge's showed its appreciation of progress so far by hosting a champagne reception in the part-excavated first basement level © Arup

An ingenious modified piling rig was used to create adjoining concrete walls around the perimeter of the new basement below. The rig was converted to electric operation to reduce noise and pollution, and had a reduced height mass to fit within the basement, but was still capable of drilling to a depth of 20 metres. Excavation and construction of the remaining basement levels then proceeded using fairly conventional top-down construction.

Health and safety management was paramount throughout. There were no reported injuries or accidents from any of the tunnel and shaft mining or the top-down construction, and no incidents involving loss of time for workers.

With construction of the 'shell' of the new basement completed at a cost of £35 million, all the machinery that services the hotel will be transferred from the top floors to basements four and five, the lower levels of the new basement, which will also be used for storage. This frees up space for up to 40 new bedrooms. Basements one and two, at the higher levels, will be fitted out to include two swimming pools, a restaurant, a spa and meeting rooms. Basement three will house operational space for hotel services, including food preparation.

This remarkable project has demonstrated that – with factors including the right site conditions, client and approach to risk – almost any historic building can be expanded downwards, without the need to shut down operations during construction. Most importantly, it requires a collaborative working relationship between the contractor and consultant, with experienced and knowledgeable engineers to do this type of work.

BIOGRAPHIES

Jim Mackey is Project Director for McGee.

Michelle Mackey is Project Engineer for McGee.

Dinesh Patel is a Director and Geotechnical Engineer at Arup.

Andy Pye is an Associate Director and Structural Engineer at Arup.

BODIES OF WORK

Professor Sir Saeed Zahedi OBE RDI FREng

When Professor Sir Saeed Zahedi OBE RDI FREng was looking for a way to combine his qualifications in mechanical engineering with an interest in medicine, biomedical engineering had just a few academic research groups. Today, as Chief Technology Officer and Technical Director of Blatchford Group, the UK's leading biomedical engineering company, he runs the team that developed the first integrated prosthetic leg. He talked to Michael Kenward OBE about a career that has transformed lives.

Much as he enjoys winning awards for engineering and personal honours, ask Professor Sir Saeed Zahedi OBE RDI FREng to recall his most satisfying achievement, and he cites assembling and managing the team that developed the world's first integrated prosthetic leg. Still an unmatched example of biomedical engineering, the Linx was the first microprocessor-controlled lower limb prosthetic where the foot and knee continuously 'talk' to each other. In this way, the Linx can create a more natural leg movement. With its combination of new materials, microprocessor controls and understanding of how people walk, Linx won the 2016 MacRobert Award. It has since gone on to restore mobility to more than 500 individuals a year [see *An intelligent prosthetic*].

This revolution in prosthetics started when Sir Saeed assembled a team of mechanical engineers, electronic engineers, and physiotherapists, among others, to work together on Linx at Blatchford Group. "Watching 30 people is almost like conducting an orchestra," he says. "You're not even telling them what to do, you are just pointing towards what they need to do."

Biomedical engineering was hardly a mainstream subject when Sir Saeed decided to improve his qualifications so that he could help people who had lost limbs in accidents and conflicts. Looking for somewhere to add a master's degree to his background in mechanical engineering, he had the choice of just two universities in the UK and there were few students keen to work in the area: "In my year, there were nine students and 16 lecturers."

LEARNING ENGINEERING

Sir Saeed ascribes his own introduction to engineering partly to a need to find a subject to study where language would not be a hindrance. Born in Iran, his first language was Farsi. When his family decided that he should continue his education in the UK, he picked A-level subjects with mathematics at their core. He considered medicine, but the advice was that it required, as he puts it now, "a greater command of English".

Like many engineers, Sir Saeed knew little about engineering when he was considering his future career. He did have an early interest in how things worked and his father bought the local equivalent of *New Scientist*. "Reading it was a natural interest in engineering, without knowing what engineering really was," he says.

When it came to looking for a career, he started by eliminating the things that he did not want to do. "I knew that I wasn't going to be a businessman, or a lawyer, or an economist, or go into literature." Mechanical engineering won the competition. Looking back, he says, as a youngster he had been interested in recycling and biomedicine, attracted by the human social benefits they offered.

After A levels, he attended the Polytechnic of Central London (now the University of Westminster) to study

AN INTELLIGENT PROSTHETIC

When Sir Saeed Zahedi and his team of engineers at Blatchford won the 2016 MacRobert Award for the Linx artificial limb, they raised the profile of prosthetics and biomedical engineering. Linx stands apart from other prosthetic lower limbs in its complexity. It is the first, and so far only, integrated prosthetic lower limb, with four microprocessors: one for the knee, one for the ankle, one for battery management and a central computer.

The work that led to the award-winning device started in 1989 when the company created the first limb with a microprocessor controller in the knee. Through the 2000s, the company began developing innovative joints that produced smoother gait and better control, and the addition of independent movement to the heel and toe of the prosthetic limb created far more fluid movements. If the wearer is walking down a slope, for example, the system recognises the angle from the sensors around the limb.

Biomechanical analysis carried out by Blatchford showed that changes in resistance of the knee joint influenced the ankle-to-foot joint and vice versa. This led to a 'brake' mode being developed that not only worked to stop the knee sinking forward on a downward slope, but also acted in the ankle to reduce the amount of momentum transferred to the next step by 42%. This means amputees can put less effort into resisting gravity as they descend and gives them a sense of stability and support as they walk downhill.

In 2010, the company introduced the first hydraulic ankles; later on, these were given their own microprocessor to control the amount of energy that they could absorb and release. For an above-knee amputee wearing both an artificial knee and ankle, the limbs would contain two 'brains' that each independently controlled the movement of each joint. However, the Linx is the first prosthetic limb to integrate the control of the knee and ankle together and produce a far more natural movement.

By combining these technologies, Blatchford believes it has been able to reduce by half the amount of extra energy a person wearing a prosthesis needs to expend to compensate for the lost limb. For example, the first microprocessor-controlled knee reduced energy expended by the wearer by 25%. Adding a microprocessor to the ankle reduced it by a further 18%, while integrating the control of both joints with a single processor in the Linx took it down by another 8%.

Read more about the Linx limb in issue 68 of Ingenia *('Intelligent prosthetics', September 2016)*

The 2016 MacRobert Award-winning Linx limb system, developed by Blatchford, is the first ever prosthetic limb with integrated robotic control of the knee and foot, in which the sensors work together so that users can walk, balance and be supported on all types of terrain © Blatchford

mechanical engineering. Polytechnics, with their roots in engineering and focus on vocational studies, gave graduates industry-friendly courses and professional qualifications. The polytechnic also gave students access to advanced manufacturing systems, through the college's links with companies such as Short Brothers, where Sir Saeed spent time learning about computer numerical control (CNC) programming and making parts for aircraft.

Sir Saeed's degree offered biomedical engineering as a final-year option, so while he investigated the use of CNC, he also did work with Northwood Park Hospital using force platforms, which are instruments that measure the ground reaction forces generated by a body standing on or moving across them, to quantify balance, gait and other parameters of biomechanics.

"When I finished my degree, I had a choice of going for a job in Short Brothers or doing a master's in biomedical engineering at the University of Strathclyde", one of the two places in the UK that ran courses in biomedical engineering.

At Strathclyde, Sir Saaed's ambition was to apply CNC technology to custom-build hip replacements. However, his supervisor and mentor, Professor John Paul FREng FRSE, suggested that the health service and technology was not ready at the time and guided him into work on lower-limb prosthetics. In part this was down to the state of the subject; biomedical engineering had yet to become fashionable. Sir Saeed recalls checking a government website and seeing that it touted biomedical engineering as the "number one topic for promoting careers in engineering". This sort of thinking led to a flood of undergraduate degree courses in the subject, and Sir Saeed may have helped that along, having worked with universities to create some of those courses.

In biomedical engineering, it helps to have experience in the medical domain. For Sir Saeed this began after he completed his master's and took up a job as a research assistant in Strathclyde's Department of Bioengineering working on a PhD on the alignment of artificial legs. This was followed by a further three years as a research fellow working on motion analysis – how people walk. It was good experience of how to gain knowledge and science, and how to apply that "into a real practical proposition".

ENGINEERING IN THE NHS

A key aspect of this time was working with patients. After six years in academic research, he moved to the NHS where he came up against another indicator of the state of his subject. The NHS did not have biomedical engineer grades, so he was told that he was a medical physicist. His role was to develop research and to manage engineering for the NHS in Dundee.

Sir Saeed's next change highlights an important issue in how biomedical engineering fits into healthcare. At the time, Scotland brought together all the activities that required biomedical engineers, including prosthetics, artificial limbs, wheelchairs and orthotics, the latter of which involve assistive devices such as braces, footwear and other services that help people to recover from or avoid injury. "The department was effectively employing professionals in parts of the multidisciplinary team to care for a varied population of people with disabilities," he says.

This was before competition began to influence healthcare. Suppliers tendered for contracts and carried out work commissioned by the NHS. The supplier then billed the NHS on a cost-plus basis. It may have been a simple system, but Sir Saeed admits that "it wasn't an impetus for developing technology".

The arrival of competition in the NHS began to change things with the medical side separating from social care, so biomedical engineers were no longer covering the whole area. This prompted Sir Saeed to think moving into the private sector, where he could indulge in some of the engineering innovation that the field needed.

He was already familiar with Blatchford, one of the UK's leading suppliers of lower-limb prosthetics and other devices. Brian Blatchford, a design engineer and a third-generation member of the family owned business, had been a visitor to Strathclyde, and had seen the need to apply engineering to prosthetics. The artificial leg had not advanced much in thousands of years, says Sir Saeed. "The most radical change was at the turn of the 20th century," he adds. "The US Navy was essentially doing research and providing articulated ankles, but it was still very much a wooden leg, a Long John Silver type of device."

CHANGING LIVES

These were interesting times for Sir Saeed. In quick succession, he was due to get married and had to choose between two job offers, which also meant moving house. "At that age, you have a lot of energy, so somehow things worked out," he explains. "I ended up moving to Blatchford as coordinator of research and development (R&D)." There he could follow up Brian Blatchford's idea of mass producing lower-limb prosthetics, and providing extra functionality by applying engineering principles and designed articulated joints as standard items. "Modularity meant that you mass produced knees and ankles, rather than making them individually," he adds. "Then you put them together like Meccano and make the interfaces for the individuals."

The move to Blatchford meant that Sir Saeed could get stuck into R&D for prosthetics. "At once, I saw that my role was to bring in the knowledge and science gained working in the university." He had a staff of around 30 people, who not only worked on new prosthetics but also the next generation of mass-produced engineering. "Suddenly, you find yourself uniquely positioned," he adds. "You have academic and clinical experience, and now you're working in industry. In those days, in our field, having this combination of three was often unheard of." One surprise, he recounts, is that at Blatchford "you could cut across all of the noise about profit and focus on the user." This was an ideal environment to develop the concept of patient experience and user-centred design.

An important part of that process involved understanding how individuals walk. Simple prosthetics could not adapt to the way an amputee walked. An artificial leg swung at a constant rate, forcing the wearer to adapt how they moved, so that it was obvious when someone was wearing a false leg.

"Despite spending six years studying biomechanics and amputee locomotion and four years in the clinic, it didn't dawn on me that, if I am going to get up from here to go to that door, I change my speed five times," Sir Saeed explains. "We now understand a lot more about what you need, as an amputee, to get up from a chair, what you need to stand, what you need to be able to stand on a slope, come down the stairs, go up the stairs." That knowledge all fed into Blatchford's development programme.

Sir Saeed's arrival at Blatchford also coincided with a change in the thinking about what amputees could achieve. Soon after joining the company in 1988 he went to Japan to see the first amputee running 'leg over leg', with both feet off the ground. "Amputees never thought that they could run," says Sir Saeed. By 2012, hundreds of amputee runners had participated in the Paralympics, breaking records in the process.

Another change around the time that Sir Saeed went to Japan was the rising number of injured soldiers returning from the Gulf War. Much of the impetus, and the knowledge that drives innovation at Blatchford, comes from working

Professor Sir Saeed Zahedi OBE RDI FREng (centre) with the Blatchford team that won the 2016 MacRobert Award

with injured soldiers at the Defence and National Rehabilitation Centre in Nottinghamshire. These patients are especially demanding of their prosthetics. As Sir Saeed describes it, their attitude is that when they had a below-knee amputation "it was just a scratch".

These factors helped to change the shape of prosthetics. As Sir Saeed sums up the situation: "The equipment is there, the motivation is there and the support is there, so you have these key factors. If they come together then everything is possible."

FUTURE OF MOBILITY

These possibilities do not stop with amputees. There is now growing interest in the broader area of mobility for people with disabilities. Sir Saeed is also involved in the World Health Organization's (WHO) GATE initiative (Global Cooperation on Assistive Technology), a 10-year programme that includes mobility as its number one topic, encompassing prosthetics, orthotics and wheelchairs. WHO estimates that "more than two billion people will need at least one assistive product by 2030". As Sir Saeed sees it: "literally one seventh or one eighth of the population will be disabled or aged. They need assistive technology devices, they need mobility devices to be able to go from A to B and be independent."

One challenge that Sir Saeed highlights is the perceived high cost of mobility aids. He points out that these devices can pay for themselves. "If people are mobile they can have a more independent life. Not only can they look after themselves, they can contribute to society."

For that to happen, prices must come down. Advanced prosthetics and orthotics are not cheap. While those in medical circles may be prepared to pay £50,000 for an artificial heart, there is a reluctance to spend a lot on prosthetics and orthotics. Once again, the split between medical treatment and social services comes into play. At the moment, there are three different pots of funding for prosthetics and orthotics in the UK. NHS England looks after prosthetics, hospital commissioning groups handle orthotics and social services are in charge of wheelchairs. "In Norway,

Blatchford covers all bases and ends up working with different agencies. "We not only design and manufacture products, we look after one-third of the amputees in the UK," Sir Saeed says. "We are service providers to the NHS."

there is one combined funding pot," which makes sense to Sir Saeed. "You need that medical care, but you also need, more importantly, social care."

Blatchford covers all bases and ends up working with different agencies. "We not only design and manufacture products, we look after one-third of the amputees in the UK," Sir Saeed says. "We are service providers to the NHS." This gives Saeed an invaluable resource. "I have access to 250 clinicians, who are a part of my team. I have access to 14,000 amputees so I can get their opinions directly."

ENGAGING THE PUBLIC

One unexpected spinoff from Blatchford's activities is the publicity value in prosthetics. When the company started using carbon fibre in artificial legs, the media rushed to write about it. Sir Saeed is happy to exploit this interest in the wider cause of engineering. Like many eminent engineers, he is frustrated by the perception of engineers. He recalls that, as a student, he was president of the university's engineering society. "One of the things that was quite strange and difficult to understand was why society saw engineers as effectively advanced plumbers or electricians, whereas the lawyers and doctors were different." Thirty years on and he believes "the same applies".

A knock-on from this misperception is that too few students think 'engineering' when trying to choose what to study and a career option. It turns out that bioengineering, and working with prosthetics, can help to tear down those barriers. Sir Saeed recounts his work with the University of Southampton and school students. At the end of a day's activities, much of it around prosthetics, he asked for a show of hands about how many would not go on into engineering. "Two showed their hands." It turned out that those two wanted to study medicine, while the other 38 wanted to be engineers.

Sir Saeed's desire to "catch them young" kicked in when he was part of the Blatchford team that won the MacRobert Award. "The team agreed that we wanted to use it to promote engineering, and the key thing is to excite the kids." It turns out that one way to do this is to introduce them to sporting amputees running the 100 metres. Not only did the students pay attention, their teachers sat up and took notice. Teachers and pupils had an opportunity to see what engineering and people with disabilities could achieve together. "If you can nurture those brains you will get the next generation of biomedical engineers, who will not only solve this problem but much greater problems."

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*.

CAREER TIMELINE AND DISTINCTIONS

Born, **1957**. Studied mechanical engineering at the Polytechnic of Central London, **1975–1978**. PhD in biomedical engineering at the University of Strathclyde, **1978–1984**. Awarded an OBE for services to the prosthetics industry, **2000**. Joined Blatchford Group as Head of Research and Development, **2004**. Appointed Technical Director at Blatchford Group, **2006**. Fellow of the Royal Academy of Engineering, **2012**. Appointed Royal Designer for Industry by the Royal Society of Arts, **2013**. British Healthcare Trades Association Lifetime Achievement Award, **2013**. Knighted for services to engineering and innovation, **2017**. American Orthotic and Prosthetic Association Lifetime Achievement Award, **2017**.

A NEW WAY TO MAKE MUSIC

A team of engineers has developed a range of instruments that is changing the way people make music. ROLI combines digital technologies and pressure-sensitive silicon so that users can generate sounds with the lightest touch.

In 2009, designer, musician and inventor Roland Lamb was studying at the Royal College of Art when he decided to create a digital musical instrument that did not have the limitations of a keyboard, for example only producing one note at a time, but still had an acoustic feel.

Using his Seaboard design, musicians can play between the 'keys' of a keyboard to produce a wide range of sounds, which are all entirely digital. It has a tactile and pliable silicon coating that allows people to play it easily in sweeping and sliding strokes. Different pressures affect the sounds, and different parts of the keys can be pressed to change notes. For example, it can simulate the effect of wiggling a figure on a guitar string to create different notes.

The design consists of a top layer of silicon (similar in consistency to a wetsuit or stress ball) that is stacked on top of a sensor board. The silicon diffuses pressure from the player's touch to activate sensors beneath the silicon that transform touch into sound. Each sensor corresponds to different notes or tones and sends messages in MIDI (Musical Instrument Digital Interface – the computer language that allows computers and digital instruments to communicate) to pass the sounds through the speakers in a matter of milliseconds.

Lamb worked with a team of electronic, software, design, sound, and quality assurance engineers to perfect the range of products that make up his ROLI line. It has various instruments, including the piano-like Seaboard, as well as 'Blocks' that can be used in a similar way to drums.

The Seaboard's silicon touchpad allows users' fingers to glide effortlessly over the sensors © ROLI

The software works with desktops and smartphones via Bluetooth.

While sensors and high-performance silicon are used in many products, combining both and integrating them with MIDI software was a challenge. The team spent four years on research and development between the original sketch and launching the first commercial product, creating prototypes and experimenting with suppliers and components.

As well as engineering a suitable surface, one of the biggest challenges was changing people's perceptions about what a musical instrument is – music has been written for certain instruments for hundreds of years. Getting the instruments in the public eye was essential. World famous musician and record producer Pharrell Williams (who has invested in ROLI and is also its Chief Creative Officer), Stevie Wonder and Hans Zimmer are among its users, and Ryan Gosling's character in *La La Land* plays a Seaboard. Several schools have integrated the instruments into their curriculums, with primary and secondary schools, and universities using them. The company is keen to teach children young, before they have preconceptions of what an instrument is. Tens of thousands of people now own and play ROLI instruments, and the number is growing every year.

For more information, visit **roli.com**

HOW DOES THAT WORK?

SPEECH RECOGNITION

Speech recognition is a machine or program's ability to recognise spoken words and phrases and convert them into a machine-readable format. The software is now a common feature in several devices, including smartphones, computers and virtual assistants.

Speech recognition is an intricate area of computer science, using a mixture of complex linguistics, mathematics and computing. It has been revolutionised in the last decade or so by the application of artificial intelligence (AI) and is by far the largest current application of AI.

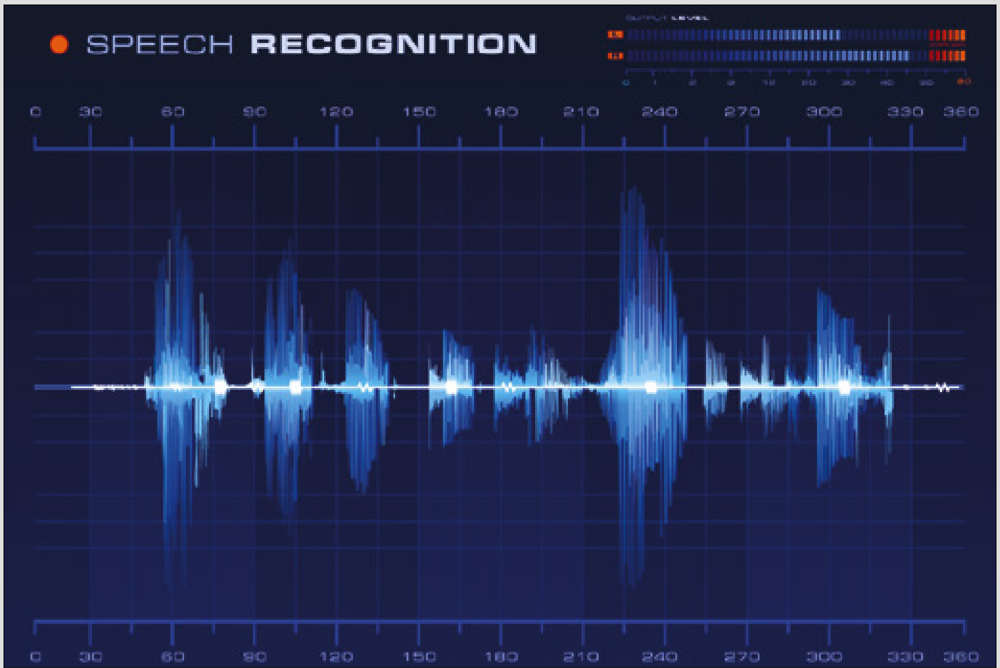
In simple speech recognition software, such as automated telephone systems used in call centres, the computer is trained to recognise a very small number of words, such as yes, no and numbers. It matches the sounds to preloaded patterns, and can recognise it through a range of accents.

Nowadays, computers carry out several steps to recognise human speech by digitising and processing sounds that can be matched to phonemes, the smallest unit of sound in speech (44 in English). These can be analysed to recognise them as meaningful language.

Speaking creates vibrations in the air that a microphone changes to a continuous electrical signal. An analogue-to-digital convertor converts the speech into a digital signal. It digitises the sound by taking measurements of the soundwave at frequent intervals and turning them into a digital format.

The computer processes this digitised signal to find the speech within all the captured sound; breaks it down into 'phones', small units of the actual sound, and processes these 'phones' to make them easier to compare to phonemes.

Any sound, and speech is no different, is made up of many frequencies just as a chord in music is made up of several different notes. The first two steps use signal processing techniques that identify the frequencies and their relative intensities at a point in time. Complex statistical models, and more recently AI, are used to identify the patterns within these that are speech and the 'phones' it is made up of.



Speech recognition software picks up the vibrations in the air created by speech and converts them into digital signals © Adobe Stock

The third step is to make those 'phones' consistent. When we speak, we speed up and slow down and the volume of our voice varies. To match 'phones' to standard phonemes the 'phones' are normalised – matched to a consistent rate and volume.

The program then needs to put each phoneme into the context of the other phonemes around them, allowing the computer to work out what it was likely that the user was saying. This is where AI comes in: training and statistical models help the speech recognition program recognise words that sound the same, such as 'see' and 'sea'. The context generally allows the program to work out which one is being used.

The AI task of recognising words correctly in the presence of background noise and different accents and individual speech patterns is considerable. Therefore, it is a task that cannot easily be carried out by laptops or smartphones. Popular speech recognition systems, such as those from Apple and Google, depend on passing the task of recognition to very powerful computers in the 'cloud'.

Research on analogue and digital electronics that might enable speech recognition in portable devices is ongoing but is still at an early stage.

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