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SEPTEMBER 2020 ISSUE 84

BOIL-OFF GAS EMISSIONS INNOVATION

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ROBOTIC HANDS

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Show Robot Company's Dexterous Hand
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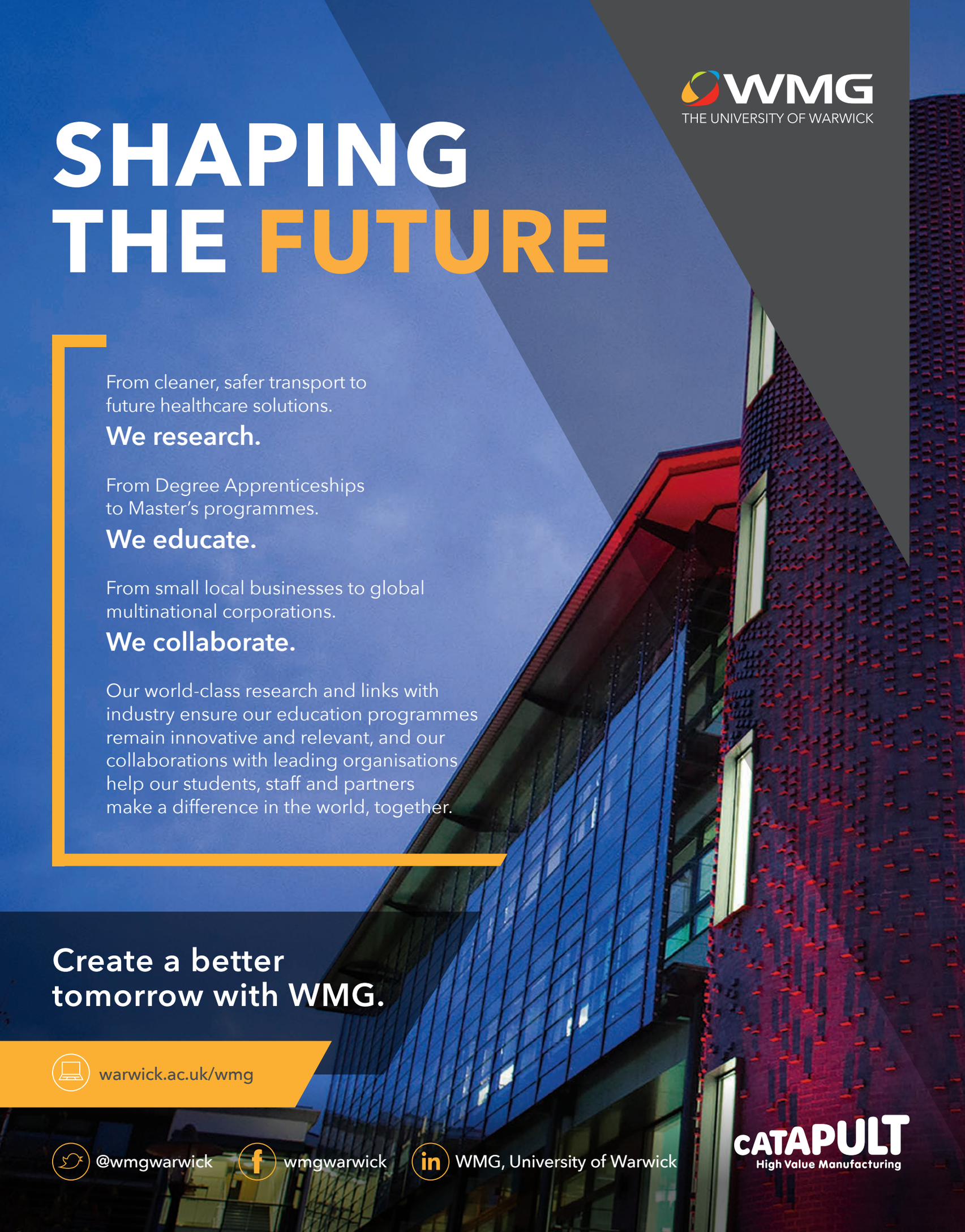
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EDITORIAL

STRENGTHENING SUPPLY CHAINS

Scott Steedman CBE FREng

Before the pandemic, we took it for granted that we could rely on global supply chains to support the UK's engineering sector. This complex web of connections between manufacturers, other organisations such as the NHS and, ultimately, consumers relies on people, information and resources. Advanced manufacturing in many engineering sectors is particularly exposed to disruption. The concept of 'just-in-time' manufacturing that has revolutionised industry over the past half century was based on having a supply chain so reliable that manufacturers could keep stock levels at the minimum.

Companies came to expect supply chains to deliver components, services and finished products as needed. No longer. The system will grind to a halt if people cannot go to work, if spare parts are not available, or services such as customs and inspection are overloaded.

For many years China has been the factory of the world. Over 200 of the *Fortune* Global 500 firms have operations in Wuhan, the centre of the original outbreak. When the city locked down, China's biggest inland port closed. Life in China is reportedly slowly returning to normal, but the impact on global supply chains is continuing.

The National Engineering Policy Centre, led by the Royal Academy of Engineering, published an excellent report in June on the impact of the pandemic, *Supply chain challenges, lessons learned and opportunities*. Through surveying 60 companies of all sizes, the centre found that many factors influenced the risk to individual firms, including which sector they worked in, their size, role and position in the supply chain, and their global reach.

Sectors such as aerospace have been heavily affected by cancelled orders and the collapse of markets as air travel came to a halt. Small companies servicing the major players in these sectors could lose everything. On the other hand, large companies with global networks may be able to keep trading in the event of a sudden lockdown by finding alternative sources of supply, even at short notice.

At the top level, many issues affect the whole industry, such as the need for flexible and adaptable logistics, common international standards that support regulatory requirements and clear guidance on safe working. As these issues are outside the control of any single company, we need a national response to strengthen supply chain resilience for the engineering industry in the UK. The Academy has a clear opportunity to push the sector and government to develop a robust strategy for the future.

Three themes have emerged where action is urgent to reduce the risk of future disruption. First, communication is vital to decision-making. Telecommunications networks are especially vulnerable. With only a small number of global suppliers (including Huawei, Nokia and Ericsson) the UK risks becoming dependent on other countries not only for components but for engineering support. Ensuring the availability of skilled, UK-based engineers who are sufficiently mobile under lockdown to maintain critical infrastructure requires forethought and planning.

Second, different sectors found different solutions to the challenges of lockdown and shortages of skills and resources. Could the food industry's experience of large-scale refrigerated distribution be a model for delivery of pharmaceuticals if or when mass vaccination is necessary? Could lessons from the offshore wind industry on safe working be relevant to advanced manufacturing? Sharing corporate case studies and preparing safety cases for networks of industry will help safeguard future production.

Third, industry needs more clarity of regulatory requirements. Under emergency powers, government relaxed regulatory requirements for testing of personal protective equipment (PPE) but there remained widespread confusion over how to bring innovative products to market. Coordinating the flow of reliable, accurate information to the sector during a crisis is essential. Alternative working practices, such as remote auditing and approval processes for priority equipment, could all be agreed between industry and regulators in advance.

It wasn't all bad. There were many individual cases of outstanding engineering achievement in response to the pandemic. Nineteen remarkable examples won President's Special Awards for Pandemic Service in August for their transformative work (see page 8). What we need now is a sector-led strategy, agreed with government, to strengthen our national supply chain resilience before the next crisis hits us.

Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

YOUNG SKATEBOARDER HOPES TO FLIP SPORT ON ITS HEAD

Charlotte with her 'Electrodeck' prototype © Institution of Engineering and Technology

Charlotte Geary, aged 13, has invented a way to help skaters move faster and do more tricks without ever having to take their feet off the board.

As part of the Institution of Engineering and Technology (IET)'s Sports of the Future competition, Charlotte from Bournemouth presented the 'Electrodeck' to judges including cycling champion Mark Cavendish MBE. The Electrodeck has a top speed of 9.5 miles per hour and is powered by a 24 V lithium ion battery and 400 W brushless hub motor. It is operated by a handheld bluetooth remote, allowing variable speed. Charlotte's design won first place and her idea has been turned into a prototype as part of the prize.

The IET's competition challenged young people to come up with a new sport or an invention that makes an existing sport even better. Competitors from across the country showcased their creative talents by submitting innovative designs. Some entries were even inspired by social distancing restrictions, including the 'Squennis Ball' that allows you to play tennis without a partner, and social distancing trainers that light up if you're within two metres of someone else.

The judging panel, which also included IET President Dr Peter Bonfield OBE FREng and IET Young Woman Engineer of the Year Ying Wan Loh, awarded second place to nine-year-old Isabella Watson-Gandy from London for 'Boing Boots' that would give her an extra spring in her step to play basketball with her older brother. The third spot went to nine-year-old Brunner Hahn, also from London, who designed a door that could be converted into a table tennis set.

QUEENSFERRY CROSSING WINS AWARD

The Queensferry Crossing has won the Royal Academy of Engineering's Major Project Award.

The Queensferry Crossing was taken from inception to completion in just 10 years. Widely hailed as an all-round success, it broke engineering records while coming in 65% under its original budget.

When the Forth Road Bridge began to deteriorate and was threatened with closure, it was vital to keep the Edinburgh–Fife trunk road open for the millions of journeys made each year. Any alternative would badly affect transport, the economy and local communities. At 2.7 kilometres long, the Queensferry Crossing is the world's longest three-towered cable-stayed bridge, Britain's tallest bridge, and Scotland's largest construction project in the 21st century. Since completion it has delivered huge benefits for the economy, businesses and local people.

The team members awarded were: Iain Murray, Executive Director of Operations at Jacobs; Mike Glover OBE FREng, Director at Arup; Peter Curran, Project Director at Ramboll; Richard Hornby, Director and Fellow at Arup; and Lawrence Shackman, Head of Rail Projects at Transport Scotland.

To read more about the engineering involved, see *Ingenia* 71, 'World record-breaking bridge'.

Queensferry Crossing © Transport Scotland

ENGINEERING ENGAGEMENT CHAMPIONS NAMED

Five new Engineering Engagement Champions aim to inspire the public and introduce more members of underrepresented groups to engineering.

The champions are funded by the Engineering and Physical Sciences Research Council (EPSRC) and will undertake a variety of public engagement activities, ranging from developing podcasts and writing children's storybooks to engaging with community groups.

The initiative aims to enhance public understanding and appreciation of the importance of investment in engineering research, with activities helping to ensure that EPSRC-funded research and innovation is informed by public concerns and values.

Professor Trevor Cox at the University of Salford will create *Inventive,* a podcast that showcases engineering and will explore different narrative approaches, interweaving factual interviews with engineers who have great stories to tell with fiction.

Dr Helen Bridle at Heriot-Watt University will work with engineers, film-makers, illustrators, storybook writers, musicians, teachers, public engagement specialists, and children to create resources, including hands-on experimental activities, for schools and nurseries.

Professor Sarah Bell at UCL is running the People's Industrial Strategy, an engineering engagement programme that will bring together engineering researchers and grassroots community groups in London to identify community priorities for research in the Industrial Strategy Grand Challenges.

Professor Lorna Dougan at the University of Leeds will create public engagement activities that allow young people and families to explore and discover innovation in materials design.

Dr Emiliano Renzi at Loughborough University will design activities to demonstrate the breadth and importance of engineering research to attract underrepresented groups to careers in engineering, and to facilitate stronger connections between schools and industry.

AFRICA PRIZE WINNER ANNOUNCED

Charlette N'Guessan is the first ever woman to win the Africa Prize and the first winner from Ghana

On 3 September, the four 2020 Africa Prize for Engineering Innovation finalists pitched their innovations to a panel of judges and a live virtual audience, with Charlette N'Guessan, an Ivorian entrepreneur based in Ghana, selected as winner. She received £25,000, with £10,000 awarded to each of the runners-up.

Charlette N'Guessan is the inventor of BACE API, a software platform that uses facial recognition and artificial intelligence (AI) to remotely verify identities. The tech entrepreneur and her co-founders developed the software after their research revealed that Ghana's banks have a significant problem with identity fraud and cybercrime, with approximately $400 million spent annually by Ghanaian financial institutions to identify their customers.

While facial recognition software isn't new, BACE API specifically uses live images or short videos taken on phone cameras to detect whether the image is of a real person, or a photo of an existing image. In contrast to global AI systems, it has been developed specifically to identify Africans.

She is the first woman to win the prize, and the first winner from Ghana.

The three other finalists come from Nigeria and Uganda. Aisha Raheem, from Nigeria, developed Farmz2U, a digital platform that reduces food waste by helping farmers plan their crops. During the COVID-19 pandemic, the disruption of traditional distribution channels has driven farmers and the rest of the agricultural supply chain online. Farmz2U has used support from the Africa Prize and the Academy's Project CARE (COVID Africa Rapid Entrepreneurs) to ensure that it is well positioned to respond to the increased demand for its services.

In Uganda, Remot is helping Ugandan schools, businesses and solar companies manage off-grid power systems more effectively. Created by David Tusubira and his colleagues, Remot examines the power system itself for inefficiencies and potential problems, monitoring the condition and performance of solar photovoltaic (PV) installations.

Also from Uganda, Dr William Wasswa's PapsAI speeds up cervical cancer screening, diagnosis and patient record management, making it more affordable and reliable. PapsAI's digital microscope slide scanner quickly scans high-resolution cervical cell images from pap smears. An accompanying analytical tool can diagnose and classify the images, and the software assesses the likelihood of a patient contracting cervical cancer given their risk factors.

The finalists were selected from a shortlist of 15 African innovators effecting positive change in their communities, who have all received eight months of training and support through the Africa Prize. All four finalists have developed innovative ways to solve global problems and are developing their ideas into businesses that can benefit entire communities.

The Africa Prize supports the brightest minds across the continent, equipping them with skills to reshape and rethink their businesses. It is the continent's biggest prize dedicated to engineering. To date, the 86 Africa Prize alumni businesses have raised more than $14 million in grants and equity and created more than 1,500 new jobs, with over 50% of these going to women and a significant proportion to people with disabilities and younger people.

LEADING POLYMER ENGINEER RECOGNISED

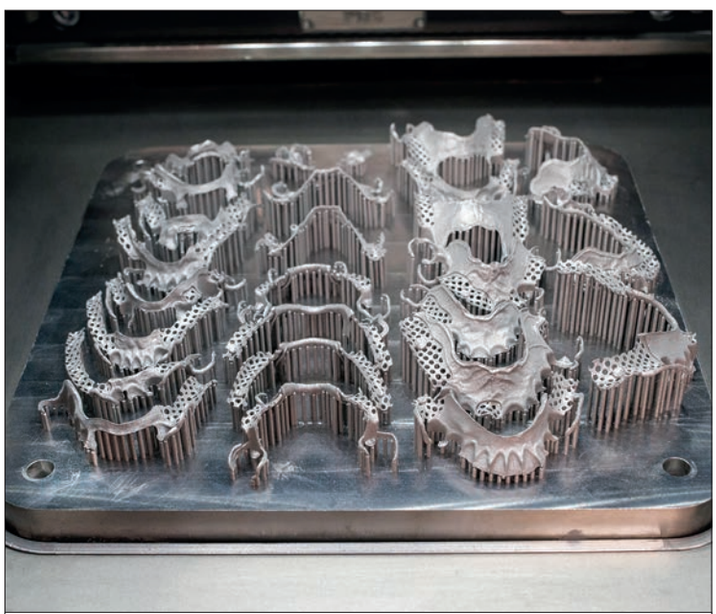
Professor Dame Julia Higgins DBE FREng FRS has been awarded the Royal Academy of Engineering's Sir Frank Whittle Medal for her sustained excellence in polymer engineering, a field that designs, analyses, and modifies polymer materials. She is internationally recognised as one of the pre-eminent polymer engineers of her generation.

A major aspect of polymer materials design and processing involves polymer blends. Dame Julia turned her attention to these important systems in the late 1980s and has worked on them ever since. She has contributed a huge amount to this research field, making a big impact on our ability to process and use polymer blends and vastly improving the design of polymer processing operations. To read more about Dame Julia and her work, see *Ingenia* 32, 'Prolific professor'.

Named after Britain's jet engine genius, the Sir Frank Whittle Medal is awarded to an engineer resident in the UK whose outstanding and sustained achievements have had a profound impact on their engineering discipline.

Professor Dame Julia Higgins DBE FREng FRS © Institute of Physics

UK IS A EUROPEAN HUB FOR INNOVATION IN 3D PRINTING



3D printed dental implants © Renishaw

A study from the European Patent Office (EPO) has shown that the UK is a leading European country in additive manufacturing (AM) innovation, also known as 3D printing.

The UK accounts for 5% of AM patent applications at the EPO, putting it in second place behind Germany with 19%. Europe is a global leader in 3D printing, with European inventors and businesses accounting for almost half of patent applications filed with the EPO between 2010 and 2018. The biggest sectors for 3D printing patent applications were health, energy and transportation, and Rolls-Royce, Renishaw and BAE Systems are the top three patent applicants from the UK.

"The surge in AM is part of the broader, rapid rise of digital technologies overall, confirming that the digital transformation of the economy is fully reflected in patent applications reaching the EPO," said EPO President António Campinos. "Europe has become a global hub for innovation in fast-growing digital fields, including AM technologies. This strength is clearly reflected in the list of top additive manufacturing applicants, with European inventors and businesses submitting almost half of the patent applications in the past decade."

IN BRIEF EXTRA

PANDEMIC SERVICE AWARDS FOR ENGINEERS

In August, the Royal Academy of Engineering awarded 19 individuals and teams of engineers with the President's Special Awards for Pandemic Service. These were awarded for exceptional engineering achievements in tackling COVID-19 throughout the UK. The winners are:

The **Ventilator Challenge UK Consortium**, an initiative led by Dick Elsy CBE to combine the knowledge and skills of 33 UK technology and engineering businesses across the aerospace, automotive and medical sectors, to produce more than 13,000 Smiths and Penlon ventilator devices for the NHS.

University College London-Ventura continuous positive airway pressure (CPAP) breathing aids, developed by a team led by Professor Rebecca Shipley and Professor Tim Baker working with Mercedes-AMG High Performance Powertrains. The team manufactured 10,000 breathing aids for use in UK hospitals and shared the designs with organisations from 105 other countries at no cost.

University of Cambridge Open Ventilator System Initiative team led by Dr Tashiv Ramsander, who developed a high-performance ventilator for manufacture in low- and middle-income countries. It became the first intensive-care-quality ventilator to be manufactured in Africa.

Jean Morris's prototype ventilator © thisisjude.uk 2020

University of Southampton for PeRSo, a respirator for healthcare workers providing a much higher level of protection than surgical masks.

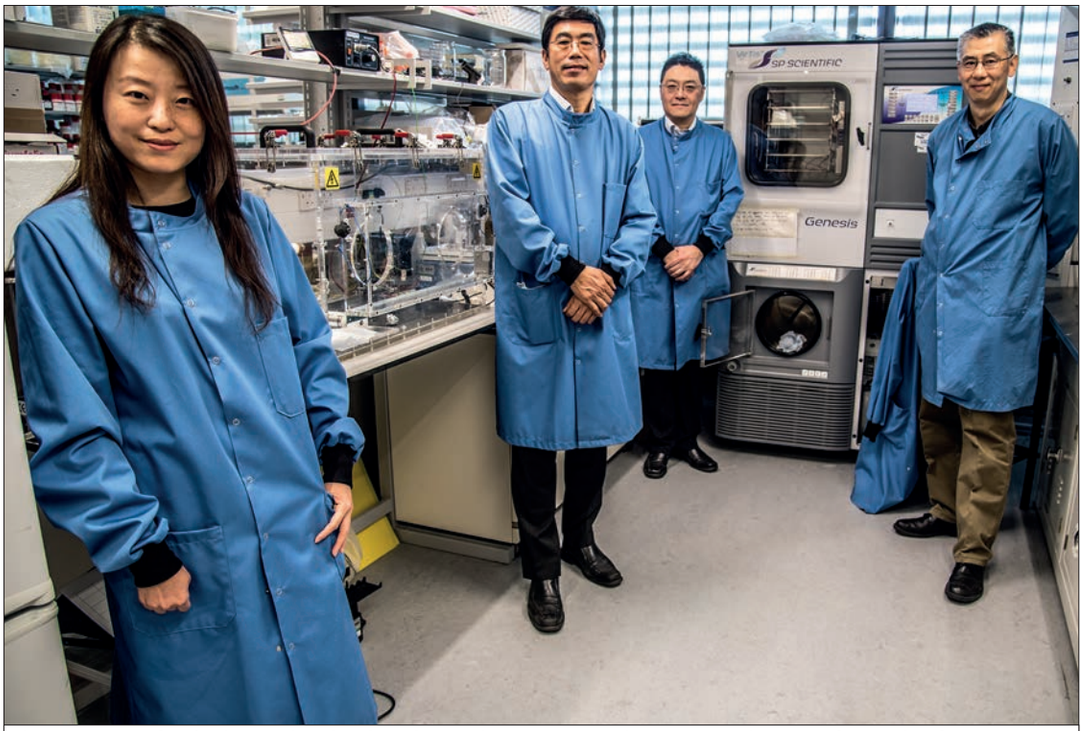
Babcock International Group Plc for the rapid development and manufacture of a new medical ventilator product, Zephyr Plus, coordinated across several major companies in the UK and Germany, with 39 suppliers and MoD logistics.

Jean Morris and a team of young engineers from the National Physical Laboratory (NPL) who took a central role in building and testing prototype ventilators against a developing Medicines and Healthcare products Regulatory Agency (MHRA) specification.

Dr Antony Robotham at the University of Plymouth for his design of an environmentally friendly face shield, manufactured from recycled materials that are compostable or recyclable at the end of life.

Dr Dominic Pimenta, a cardiology registrar at one of London's busiest hospitals, who led the design and manufacture of face shields with the team at Makerversity for frontline NHS and care home staff. His charity, HEROES, has produced 100,000 reusable face shields as well as thousands of reusable gowns and scrubs.

A team at the **Institute for Manufacturing at the University of Cambridge**, who helped local hospitals make the best use of their resources by streamlining



The University of Oxford team that developed a rapid COVID-19 test, l–r: Dr Hong Chang, Professor Zhanfeng Cui FREng, Professor Wei Huang, Dr Hui Wang © thisisjude.uk 2020

logistics for sourcing and storing vital personal protective equipment (PPE), informing decision-making on emergency demand, and developing a ventilator sharing system to be used in emergencies.

Tharsus for Bump, a social-distancing system providing real-time alerts when wearers get too close. Led by CEO Brian Palmer FREng and CTO Dave Swan, the technology's smart data insights inform rapid decision-making, allowing employers to maximise workplace capacity and providing data on team contact in the event of an outbreak.

Dr Ravi Solanki and Raymond Siems, volunteers for the charity HEROES, who, with their team, turned an idea into a platform with genuine impact in less than two days. They developed a secure website through which more than 543,000 items of much-needed support have been provided to NHS workers, from sustainable PPE to counselling services and childcare.

Professor Chris Toumazou FREng FRS FMedSci of Imperial College London for developing a rapid, affordable COVID-19 test based on a lab-in-a-cartridge technology that provides test results in just over an hour. The NHS is now deploying 5.8 million tests in preparation for the flu season.

Professor Zhanfeng Cui FREng and his team from the University of Oxford for the Oxford rapid viral RNA test for COVID-19. It can detect SARS-CoV-2 infection in 30 minutes and could be invaluable in developing countries because no specialist equipment is needed.

Professor Harris Makatsoris from King's College London for developing a 'factory-in-a-box' that allows the rapid manufacture of synthetic RNA vaccines against the SARS-CoV-2 virus and minimises the space required for high-volume vaccine production.

Professor Catherine Noakes from the University of Leeds, recognised for her role in advising the NHS and the government at the highest level during the pandemic, shaping life-saving guidance based on her expertise in environmental and engineering controls.

Sewers4COVID from the University of Exeter: a team led by Professor Dragan Savic FREng that applied machine learning to sewer epidemiology to estimate the number of infected people in a certain geographical area to track the spread of infection.

BOC Customer Engineering Services, which maintained the oxygen supplies to treat COVID-19 patients across the UK. BOC engineers set up oxygen systems at six Nightingale centres, including the largest medical oxygen system ever installed.

Matt Benson, Elliot Dervish and Jonathan Parker of Teledyne-e2v, who developed and manufactured the Handy Hook for frontline NHS staff across Essex and London, to limit their interaction with surfaces carrying the virus.

Martyn Frackelton and Ian Watkins from Mott MacDonald for project managing both NHS Nightingale London and NHS Nightingale North West, enabling the massive field hospitals to care for patients within two weeks of being announced.

In announcing the awards, Professor Sir Jim McDonald FREng FRSE, President of the Royal Academy of Engineering, said: "Engineering expertise and innovation has been central to the global fight to save lives and protect livelihoods. I am also incredibly proud of engineers everywhere who have worked round the clock to maintain essential services, critical supply chains and infrastructure in unprecedented circumstances, using their training and skills to find innovative solutions to a host of problems and to help mitigate the impact of COVID-19 on our daily lives."

To read more about the awards and winners, please visit **www.raeng.org.uk/pandemic-awards**

HOW I GOT HERE

Q&A

2020 RAENG ENGINEERS TRUST YOUNG ENGINEERS OF THE YEAR AWARDS, SUPPORTED BY THE WORSHIPFUL COMPANY OF ENGINEERS

Dr Andrea De Luca is the Founder and CEO of Flusso. He developed the core technology behind the smallest flow sensor in the world. These sensors can be used in medical, consumer, environmental, automotive, and industrial settings, for example in breathalysers, drones and fire detectors.

Ingenia spoke to four engineers who have won the 2020 RAEng Engineers Trust Young Engineers of the Year awards about their engineering journeys. The award recognises the potential of young UK engineers who have demonstrated excellence in the early stage of their career. Fifth award winner Sorin Popa, who was also awarded the Sir George Macfarlane Medal, speaks about his engineering innovation on page 43.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

Andrea: I always liked taking things apart and trying to understand how they worked. I started with my grandpa's radio … he was not very happy. Engineering was a natural choice for me.

Amy: I wasn't really aware of engineering as a career until I travelled to Lesotho when I was 17. Lesotho is at high altitude and when I was there it was very hot during the day and very cold at night, I saw people living in corrugated iron shelters and wondered why people would live in a material that conducts heat in a way that would make people uncomfortable (too hot during day and freezing at night). I thought that there must be a better solution to this that was cheap and could be locally produced. I went home and researched this and found that civil engineering is essentially solving problems like this.

Boyang: Physics and maths were my favourite courses when I was at secondary school. Engineering transforms these theories to real masterpieces, which have been revolutionary in making life better for every human.

Richard: I first got into engineering as a child. I grew up with my dad tinkering in the shed, fixing old tractors, and creating tools and machinery both for fun and a purpose. This inspired me to want to build, change and improve things too.

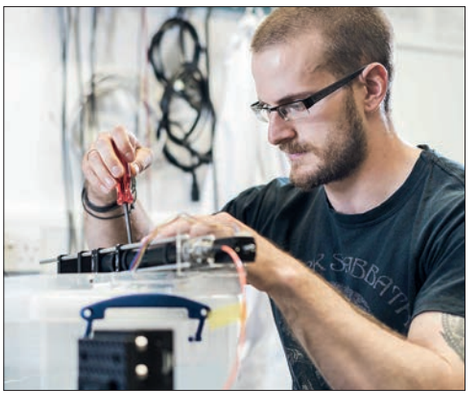
HOW DID YOU GET TO WHERE YOU ARE NOW?

Andrea: Studying a lot first and working hard later on. I had an objective and did my best to achieve it. I guess in short, by being focused.

Amy: I haven't had a straight path, but I have gained great experience learning from different companies and in different roles. I applied to work on the Northern Spire bridge, which is my proudest achievement. I worked as a senior engineer as part of the construction team, and was selected to be part of the panel that was responsible for choosing name options for the bridge,

Amy Wright is a senior civil infrastructure engineer at Design ID. She previously worked for Farrans Construction where she was a key member of the delivery team for the £118 million Northern Spire cable-stayed bridge. Amy has previously volunteered on development projects in Malawi and Kenya and has worked with the Institution of Civil Engineers since 2013 on outreach work, creating activities and working in schools.

Dr Boyang Shen holds a Research Fellowship at Clare Hall and is a Research Associate at the University of Cambridge. He has published 60 peer-reviewed journal articles. He made a significant contribution to the electromagnetic characteristics of high-temperature superconductors, and the design of medical imaging devices that help early detection of diseases that involve variations in human tissue.



Dr Richard Colchester is a Research Fellow at UCL, where he has been instrumental in developing all-optical ultrasound for minimally invasive medical devices. The devices that he is developing provide real-time imaging with structural and molecular contrast from within vessels, including coronary arteries to guide stent placements.

which was opened up to the public vote. I have just followed my instincts with regards to jobs and this has led to me working on some amazing projects and getting a wide range of experience that has given me insights into all aspects of civil engineering.

Boyang: I did my bachelor's, master's, and PhD degrees in the UK (Cardiff University, Imperial College London and University of Cambridge), all in engineering topics. Therefore, it was fairly natural to carry on my research in engineering.

Richard: With the help, guidance, support, and inspiration of a lot of people. I'm very fortunate to have had excellent mentors.

WHAT'S YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

Andrea: I love the creation aspect. Having an idea and seeing it materialising gives me a nice rewarding feeling.

Amy: I am constantly building my skill set and gathering experience so I can be really useful in helping people. My ultimate aim is to have a long-term role in development engineering and each step I take is collecting ways to be most useful to a social enterprise or charity one day. Every problem I solve teaches me a lesson that I can add to my experience that will be useful in the future.

Boyang: Engineering is always inspiring and rewarding. Sometimes engineering is challenging, but when you solve the problems it can be great fun.

Richard: My favourite thing about engineering is that I get to play, build, and invent new things for a focused and worthwhile cause. It's like Lego for adults, but with an end point that will hopefully improve the lives of other people.

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

Andrea: Just do it. I am writing with a laptop, looking at a second screen, my mobile phone is at my left and I can hear noises from cars, airplanes and TVs … The work you will be doing might shape to world we all live in!

Amy: Get all the experience that you can, there is a wealth of opportunity out there and people who are happy to help or point you in the right direction. Be proactive and keen and people will see that you are interested and your enthusiasm will shine through. Don't be afraid to make mistakes – I have certainly made a few!

Boyang: Jobs in engineering are always in demand all over the world. Engineers benefit from jobs that pay well and are respected, and more importantly, engineering equips you with logical ways of thinking that are extremely valuable throughout life.

Richard: Go for it! Don't be afraid to ask for help and support and don't be afraid to try new things, this is how breakthroughs are made.

OPINION

WHAT PRIMARY SCHOOLS CAN TEACH US ABOUT SKILLS FOR ENGINEERING

A shortage of STEM graduates and skilled workers is costing the UK significantly and this skills gap is due to worsen over the next 10 years. There are many challenges in providing a solution. Dr Susan Scurlock MBE, CEO and Founder of Primary Engineer, believes there is room for a fundamental shift in the way education supports the development of key STEM skills, which will help plug this gap.

Dr Susan Scurlock MBE

The UK has had a perennial problem in attracting young people to study science, technology, engineering and medicine (STEM) subjects. This then leads to a shortage of STEM graduates and skilled workers. In 2020 that shortage cost the UK over £1.5 billion a year, with some studies suggesting an annual shortfall of around 173,000 workers. To plug that gap, we need a fundamental shift in how education supports the development of STEM skills.

Employers' skills needs vary widely, depending on the workforce and the industry. Currently, the government does not gather robust data on STEM skills, making it difficult for schools to understand where to focus their energy. However, we do know that, while knowledge of STEM subjects underpins everything, businesses also look for a combination of complementary skills.

The wish list is long, including skills in leadership, communication, creativity, problem-solving, and project management. Then there are more specific STEM industry skills, such as management, engineering, testing, communications, security, and IT. If we are to begin to develop these skills in young people, we must provide them with opportunities to develop those skills throughout their education. These opportunities should be in the form of 'meaningful experiences'.

Meaningful experiences require schools to engage students with student-centred curricula that allow the development of not just knowledge but skills over time, and where students have time to reflect and improve. To make this work, we need an integrated approach to STEM education, where learning is interactive, cooperative, collaborative, and takes place through inquiry-based or problem-centred models. These models are designed to trigger enthusiasm and curiosity, through moving responsibility to the student and allowing them to become agents of their own learning. Students can develop questions that they are hungry to answer, and teachers facilitate or scaffold the learning process, rather than lead.

This new approach to STEM education gives students the opportunity to conduct meaningful projects that solve real-world problems, while encouraging the application

of STEM knowledge and skills. Asking students to identify the problems and to work systematically through them requires different thought processes to the more instructionist 'chalk and talk' approach, and it provides a more solid and welcoming platform for applying and developing key skills. Designing, creating, testing, and communicating innovative and creative solutions to problems also allows students to see the beauty and benefit of STEM as an educational or career pathway.

The UK has two distinct curriculum models across primary and secondary education. The primary school model lends itself to an interactive approach. Pupils can work together within the same workspace or classroom and across subjects, projects, topics, or problems. Evidence suggests that this approach allows pupils to work successfully in situations of uncertainty and makes them more adaptable. There is also evidence that primary school pupils exposed to this style of learning not only improve their curriculum knowledge but also improve their attitudes and skills such as resilience, communication, and teamwork.

These are important skills to develop in the short and long term. However, despite this clear benefit, we do not adopt the same approach in secondary education. That would require schools to take a more coordinated approach across the individual STEM subjects, with more communication and collaboration between teachers when planning curriculum models.

The new Ofsted framework for England asks school leaders to construct a curriculum that is 'ambitious'. This requires those teaching secondary science in England to have a clear curriculum vision for the subject and to be able to implement it effectively. While in reality this may be challenging, it is not impossible. Studies show that project- or problem-based learning has a positive effect on teacher confidence, control, and motivation within the classroom. This, in turn, supports the transition to a more collaborative problem-based model in secondary education.

I believe that school governors and academy trustees also have a crucial role to play and not just by supporting this new approach. They should also challenge senior leadership teams to ensure that schools expose all students to meaningful experiences across STEM subjects that are linked to important community, societal, and global issues, such as air pollution and climate change. We should encourage teacher STEM groups to reach out and form networks with local industry and their communities, where they can share ideas and support one another in this problem-based learning environment.

Industry must play its part in any educational shift. In 2018, the CBI and the educational publisher Pearson reported that the results of an education and skills survey showed that 80% of the businesses surveyed were enthusiastic about being involved in education. However, the survey also showed that the number of businesses engaged with schools or colleges was down by almost 10%. Pearson also reported that, in 2019, only 25% of UK businesses were engaging with local schools and colleges.

There are huge opportunities for better coordination of engagement between local businesses and schools to enhance the competitive advantage of regions across the UK and to help young people to understand which skills local businesses need. This approach will not only equip young people with knowledge, but with the skills they will need to succeed in an unknown future.

In this way, working with industry and education together we can create an adaptable and agile workforce. That can only have a positive effect on closing the UK's skills gap. In uncertain times, we have discovered that schools and colleges can change and adapt how they educate future generations. Aligning secondary education more closely with the project- or problem-based model, akin to that of primary schools, would be a step in the right direction.

BIOGRAPHY

Dr Susan Scurlock MBE is CEO and Founder of Primary Engineer. She founded the organisation in 2005 and, over the years, has developed a sophisticated programme of award-winning teacher training courses and helped design national competitions and educational programmes involving industry, universities, councils, and professional engineering institutions. Annually, these reach over 5,000 teachers, and involve over 2,000 engineers and 90,000 pupils. She is the recipient of three honorary doctorates and was awarded an MBE in HM The Queen's New Year's Honours list in recognition of her work in engineering education. Susan has won the Royal Academy of Engineering's 2020 Rooke Award, which is awarded to an individual or small team based in the UK that has supported the Academy's aims and work through their initiative in promoting engineering to the public.

GROUNDBREAKING DIGGING

JCB's all-electric mini excavator is ideal for work indoors, in tunnels or even underground, as there is no need to extract toxic combustion fumes. It produces just a fifth of the noise of a traditional diesel engine model, an advantage for work in busy cities – or libraries © PinPep

The world's first electric mini digger demonstrates how construction and plant machinery could finally leave fossil fuels in the dirt. Neil Cumins spoke to JCB's Chief Innovation and Growth Officer Tim Burnhope FREng and Director of Advanced Engineering Bob Womersley about the engineering behind this award-winning achievement.

Such is the 19C-1E's engineering excellence, it won the Royal Academy of Engineering's 2020 MacRobert Award

For over a century, oil has provided the fuel for most of the world's transportation. The dominance achieved by petrol and diesel seemed unassailable in the 20th century, even during the 1970s Arab oil embargo and the fuel strike of 2000.

Yet electricity has always been a viable alternative in terms of propulsion. The first electric car was developed in America in 1890, while post-war Britain echoed to the whine of electric milk floats. Sir Clive Sinclair's C5 was decades ahead of personal transportation solutions like the Segway, and over a third of the UK's rail network is already electrified.

FROM ZERO TO HEROES

With climate change one of the stories dominating the headlines before COVID-19, the necessity of moving away from fossil fuels has been acknowledged even by the internal combustion engine's most loyal supporters.

When construction equipment manufacturer JCB set out on the road to zero carbon, it was obvious that new propulsion systems would be required for its range of diesel-powered machines. Heavy machinery such as 20-tonne excavators can run on battery power, but it would be expensive to purchase and time consuming to charge, so smaller machines are much better suited. So began a multi-layered research programme, attempting to develop hydrogen solutions for larger machines while creating electric alternatives to the diesel engines fitted in the company's smaller products.

The result is the world's first fully electric mini excavator – the 19C-1E. Visually identical to the diesel-powered 19C-1, this 1,787-kilogram machine will eventually form part of a family of vehicles sharing the same groundbreaking power source. Such is the 19C-1E's engineering excellence, it won the Royal Academy of Engineering's 2020 MacRobert Award, supported by the Worshipful Company of Engineers. This award acknowledges the engineering challenges involved (and solved) in creating a construction machine capable of travelling through a library without shaking the paperbacks off their shelves.

THE POWER AND THE GLORY

The first thing to note about the electric mini-digger is its similarity to the standard 19C-1 diesel model, as JCB's Chief Innovation Officer Tim Burnhope explains. "It uses the same bodywork, but we designed it so the diesel engine could be replaced with the battery and motor. It's the same weight, so you can tow it on the same trailer. All the access points on the bodywork are identical, with a charging point where you normally put the diesel fuel in. To a customer it feels the same, and the only real difference to the operator is that the fuel gauge has been replaced with a battery level gauge." Essentially, the electric motor and batteries slot into the diesel housing and the 19C-1E is otherwise identical to the 19C-1 diesel model.

Sourcing suitable batteries was central to this project's viability, and the automotive sector provided inspiration. JCB's Director of Advanced Engineering Bob Womersley quickly recognised the advantages offered by the Sunderland-built Nissan LEAF's lithium-ion cells: "When we were introducing our machine into the market, we had to have absolute confidence in its robustness. The LEAF batteries use pouch cells, rather than cylindrical cells like the Tesla range – these have many electrical joints in the battery configuration. The robustness requirement that is unique to off-highway equipment steered us in the direction of pouch cells."

Densely stacked in space-efficient rows, pouch cells are encased in robust bags that

The 19C-1E with side covers removed shows the electrical components packaged tightly within the space of the original diesel engine © JCB

protect their contents. This addresses one of the biggest challenges facing any electric powerplant used in industrial machines. "Track laying machinery has no suspension," Bob says, "so it shakes the machine extraordinarily over rocky or uneven terrain. Machines can encounter well over 15 G, substantially higher than you'd see in a passenger car, so any tiny weakness is exposed in a digger application." These G forces (acceleration) also affected the design and manufacturing of the 19C-1E's electric motors, which have resin-encased windings to reduce vibration sensitivity. The motor connects directly to the hydraulic pump without requiring a flexible coupling, helping to reduce the transport weight.

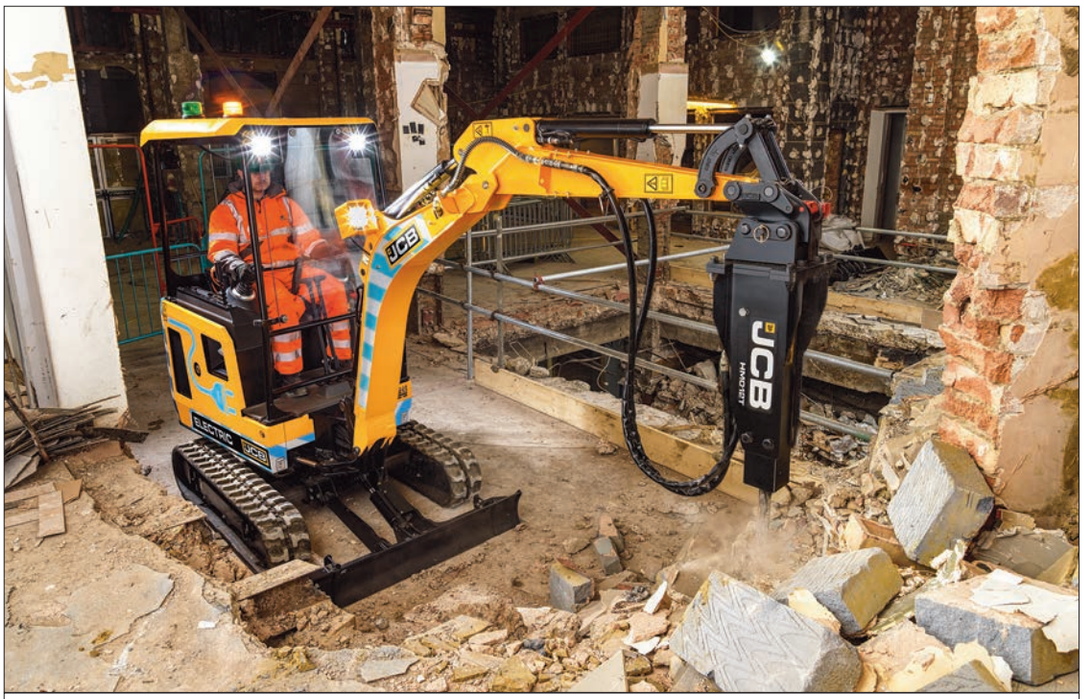
The pouch cells are assembled into 5 kWh battery packs, and the 19C-1E can currently be purchased with four packs. Each one weighs 35 kilograms, although the machine is only 3 kilograms heavier than its diesel counterpart. Compensatory weight savings include the absence of a radiator, no coolant liquid or engine oil, and of course no need for a heavy diesel engine.

IT'S GOOD TO TORQUE

With two patents pending on the electric powertrain, a 48 V electrical system delivers instant torque (a measure of the force that can cause an object to rotate about an axis) from the electric motor to the load-sensing hydraulic system. When not in use, the motor drops to an idle speed of just 150 rpm (rotations per minute) to optimise battery life. The motor only needs to idle in order for the hydraulic pump to be on standby at very low speed for instantaneous acceptance of load as the operator demands. Instant torque is available for operation at either 1,200, 1,600 or 1,800 rpm, while it's also possible to increase power to 2,300 rpm for rapid relocation between sites.

"The low idle speed runs considerably slower than a diesel engine," explains Bob, "and the torque characteristic of the motor means it can deliver the power at a much lower speed. We have a device in the control software that we call auto kick-up, which is the opposite of auto idle. This encourages the operator to work on the lowest set point on the motor speed, but when they really need high power during machine operation, the software has an auto kick-up function that means they aren't tempted to use more motor speed than necessary. Because the machine is very quiet, the operator is not aware of its operating speed, and the seamless delivery of power means they wouldn't have an awareness that these efficiency measures are going on."

Interestingly, the auto kick-up technology had been developed previously but never made it into a production machine. "We had trialled the auto kick-up as part of our machine efficiency systems," says Bob, "so it was shelf engineered but not fully refined. In fairness, it works better with an electric motor than with a diesel engine



The 19C-1E can easily and safely carry out internal works, as it produces no fumes, has no tethering cables and creates no engine noise © JCB

because of how inconspicuous it is and how quickly the motor can react to it. We refined other systems as they were tested – we changed the hydraulic circuit to minimise the pumping losses, and ran the motor slower so the pump was running at a greater displacement than it would on the diesel machine."

"One of the crucial testing stages was actually giving it to customers," admits Tim. "We got it out on site to make sure we could learn from customers very early on. That allowed us to gain knowledge and prove the concept, and I think there was a lot of surprise when we started rolling out models to test. Customers didn't expect electric to offer the same performance level as diesel. For some reason, they expected it not to deliver the same power as the diesel model and that the machine would lose power under load. They were shocked to realise just how powerful it was." Yet the 19C-1E's performance figures are comparable to the diesel model across the board, providing a maximum digging depth of 2,891 millimetres with the largest 1,344-millimetre dipper arm fitted.

ROCKS AROUND THE CLOCK

Another crucial piece of research was the accumulated telemetry data gathered from diesel machines throughout the last decade using JCB's LiveLink system, including average run times and load on equipment. The JCB team noted with surprise that many electric test models were being used for longer periods each day than their diesel counterparts, possibly because of a combination of lower operator fatigue and quieter operation permitting use outside of normal working hours.

The absence of fumes or tethering cables means internal works such as foundation excavations can be carried out safely, and the lack of engine noise enables operators to talk to people outside the vehicle even while it's in use. Indeed, one of the greatest benefits of electric power is its quietness compared to internal combustion. The 19C-1E emits remarkably less noise compared to its diesel counterpart, with almost no powertrain noise, low vibration and no diesel fumes. This makes long periods at the 19C-1E's controls more comfortable, as well as enabling it to work in busy urban environments without disrupting nearby homes and workplaces.

ELECTRIC DREAMS

During a 10-month period of the development process, the JCB team quadrupled the battery's run time, giving it the capacity to complete a full day's shift on site. Onboard telematics, a standard feature on all JCB machines, yielded valuable background information, especially while the 19C-1E was being tested in JCB's proving ground – a large quarry adjacent to the factory, where even JCB's heaviest equipment including the X-Series excavators are tested. Despite being dwarfed by its surroundings, the 19C-1E proved capable of operating at a wide range of temperatures and maintaining performance throughout the charging cycle.

Charging can be carried out using a standard three-pin mains plug, taking eight hours at 230 V. However, many industrial clients will have access to three-phase power at 415 V, which is capable of fully replenishing the batteries in just over two hours. The modular design of both the batteries and electric motor will support their incorporation into many other products within

"We've set the benchmark for volume-produced electric construction equipment," says Bob, "and in the process, we've crossed a threshold of understanding on electric propulsion"

the JCB range, while the same production line is currently fitting electric and diesel motors into the otherwise identical 19C-1 bodies.

BREAKING NEW GROUND

The 19C-1E is a domestic success story, with a proprietary electric propulsion system developed and supported by a UK-centric supply chain including battery and motor manufacturers. "We've been pleasantly surprised by the way UK agencies now have the foundation for developing electric vehicles," Bob acknowledges. "The universities have specialist equipment to test batteries, and we did a shaking test extensively on battery packs because there are safety considerations regarding fire risks. That testing infrastructure now exists in the UK, which has been really advantageous for us."

Since its launch, the 19C-1E's sales have more than quadrupled initial estimates, with exports to 32 countries. This is an entirely new market, and despite a higher retail price resulting from the cost of battery production, the electric mini-digger has a lower cost of ownership than its diesel sibling thanks to minimal maintenance and the ability to complete work that would have otherwise been carried out by hand or with the support of expensive fume extraction. Bob cites an example of a contractor trialling the 19C-1E on behalf of a utility company: "It was quite a delicate assignment, because when it comes to working beside a water main, you usually need to finish off with a spade. Without engine noise to distract him, the operator could hear the teeth touching the cast iron water valve. He was very surprised!"

Indeed, consumer scepticism is one of the few challenges facing JCB as it rolls out this new technology. The utilities contractor was initially doubtful about the electric digger's potential, and similar concerns are shared among other prospective clients. "There isn't a conscious resistance among customers," Tim says, "just nervousness. Any innovation needs leaders and ambassadors to start removing the blocks to its adoption. We need more hire companies to take the product so people can try it without capital commitment. Good news travels fast, and once people experience it, they get more confident and tell others."

"We've set the benchmark for volume-produced electric construction equipment," says Bob, "and in the process, we've crossed a threshold of understanding on electric propulsion. We understand batteries, we understand electric motors, we understand the control system and the electrical architecture to deliver the power. It's almost like we've come of age, and we can see the route to capitalise on it."

Tim concurs: "We've got an electric machine solution, with a modular battery system and motors that can be rolled out across many products in our range. We have the infrastructure to go up through the weight classes with electric products. Imagine if you buy several different products at the same time, and they all have the same technology. It'll all be interchangeable." At the current rate of progress, it won't be long until we see many more electric-powered construction machines on sites across the world.

BIOGRAPHIES

Tim Burnhope FREng is Chief Innovation and Growth Officer at JCB. Prior to this, he held numerous roles at the company including Group Managing Director of Product Development, MD of JCB Sales, Director of European Sales, and MD of both the Loadall and Backhoe Loader Business Units.

Bob Womersley is Director of Advanced Engineering at JCB. He joined JCB in 1982 as a development engineer on JCB's first production transmission, and his positions at the company have included Chief Engineer, Engines, and Director of Hybrid programmes. As Advanced Engineering Director, he has led JCB's strategy on machine electrification and advanced propulsion.

AIR-BREATHING ROCKET ENGINE

Successful completion of high-temperature tests of a unique precooler system for jet engines could be a key breakthrough in space travel. A team from Reaction Engines devised the test programme and won this year's Royal Academy of Engineering Colin Campbell Mitchell Award. Hugh Ferguson talked to Dr Helen Webber, engineering project lead, about the significance of this development, which could also have important applications closer to Earth.

SABRE technology could allow launch vehicles, such as a SABRE-powered spaceplane, to have aircraft-like operation © Reaction Engines

Each year there are about 100 launches into space worldwide (compared to 100,000 flights per day on average), despite the growing demand for Earth-orbit operations such as communications and meteorology, and the desire for exploitation of the Moon and exploration of Mars and beyond.

For decades, the principal constraint on growth has been well understood. Despite efficiency improvements, escaping the Earth's gravity and getting into low Earth orbit is still extremely expensive, requiring large, fuel-guzzling, multi-stage, single-use rockets carrying relatively small payloads: around 90% of a space rocket's weight at launch is propellant. As a result, each launch typically costs around $100 million (payload dependent), there are long waits for 'slots', and the failure rate is generally between 2% and 5%.

The founders of Reaction Engines wanted to devise a hybrid jet/rocket engine to power a single-stage, fully reusable launch vehicle able to take off and land horizontally on an airfield, which could cut the costs of reaching low Earth orbit by a factor of 10 as well as enabling a fast turnaround of the vehicle.

The essential difference between jet and rocket engines is that a jet draws in air (and therefore oxygen) from the atmosphere to help fuel combustion, and therefore doesn't have to carry it on board while the jet engine is in operation. By contrast, a rocket carries all its own fuel, including liquid oxygen, most of which is consumed in multiple stages during launch. This is the only option in space where there is no oxygen. This mass saving in jet engines enables a transformation in the vehicle design (a rocket into a 'spaceplane'), with the implementation of heavier systems such as wings and undercarriage. The 'dream' is to create a vehicle that uses a jet at low levels and speed – up to Mach 5 (five times the speed of sound) at around 26 kilometre altitude – and then switches to rocket power to reach orbital velocity (around Mach 25).

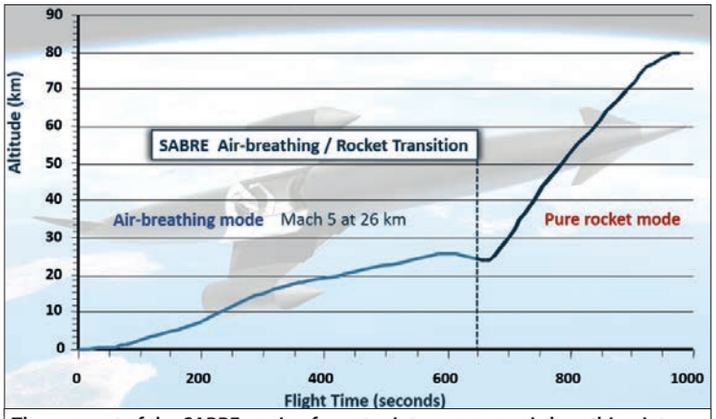
The greatest challenge is devising a very lightweight jet engine that can operate at Mach 5, two and a half times the speed of Concorde and much faster than the world's fastest jet, the Lockheed SR-71 Blackbird at Mach 3.3. Hence Reaction Engines' SABRE (Synergetic Air Breathing Rocket Engine), the world's first air-breathing part jet, part rocket engine, which relies on an innovative precooler heat-exchanger technology. Finding a practical way to cool the air entering the turbo-compressor to a temperature that the engine can withstand and operate efficiently in proved the most challenging aspect of the engine itself.

At these speeds, due to compression effects, the air entering the housing around the engine would be at around 1,000°C, the temperature of molten lava and sufficient to melt parts of the engine. If this could be reduced rapidly to ambient sea-level temperature, then heat-resistant and generally heavier alloys could be avoided in the engine, and performance could be greatly improved: cooler air means a higher compression ratio and a more efficient engine.

But how do you design an ultra-lightweight precooler heat exchanger that can cool air from 1,000°C to ambient in less than 0.2 seconds (the blink of an eye)? And how do you then test it – without the time and expense of building the whole engine and testing it in flight – when nothing like it has been attempted before?

COOLING DOWN

For a spaceplane, the precooler needs to achieve



The concept of the SABRE engine for entry into space: an air-breathing jet for horizontal take-off and flight up to Mach 5 at 26 kilometres altitude, and rocket mode beyond © Reaction Engines

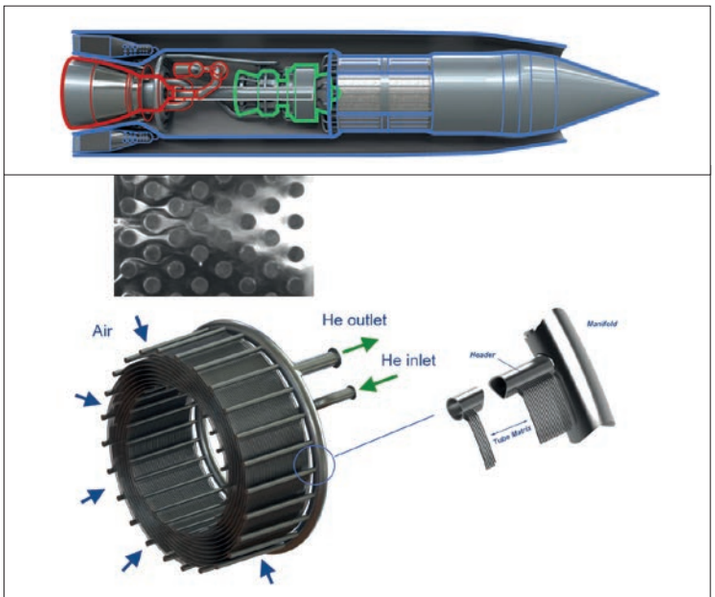
REACTION ENGINES

In 1989 Alan Bond, Richard Varvill and John Scott-Scott, three Rolls-Royce engineers frustrated by the decision to withdraw funding for development of the British HOTOL (horizontal take-off and landing) project for a single-stage-to-orbit spaceplane, left their jobs to form their own company to continue development themselves. Inevitably, they became known as 'The Three Rocketeers'.

Initially, their goal was development of the Skylon space plane, but efforts became increasingly focused on its key element – the SABRE engine and, in particular, its precooler heat-exchanger technology. Partners were brought on board and the company is now supported by the UK government, UK Space Agency, and European Space Agency and its US team is working with the US government and industry partners. It has also received investment from BAE Systems, Rolls-Royce and Boeing HorizonX, and has contracts with the UK's Ministry of Defence and the US Defence Advanced Research Projects Agency (DARPA).

Individual components of SABRE (including the precooler) have been successfully tested, and more are to follow. The company is progressing plans to demonstrate hypersonic systems enabled by this precooler technology and to undertake ground-based tests of the SABRE engine core, culminating in full system testing.

The company now has more than 200 staff based at Culham and its US facility in Denver, Colorado. Recent initiatives include establishment of an applied technologies team to exploit the company's innovative heat exchange systems through application in a wide range of commercial industries.



The three main elements of the SABRE engine, each being developed in parallel under separate programmes: the housing (blue) including a bypass ramjet and the crucial precooler; the air-breathing core engine (green); and the rocket system at the rear (red). Bottom: The HTX test version of the precooler showing the spiral arrangement of tiny tubes carrying the helium coolant. Hot air enters radially from the outside and exits to the rear towards the turbo compressor © Reaction Engines

around 400 MW heat transfer, equivalent to the output of a large power station. The Hot Heat Exchanger test programme (HTX) version is smaller and only requires 3.8 MW – which is still equivalent to the power required for 4,000 homes – although in most other respects it is the same as the full-scale version, and operates in the same conditions, including temperature and pressure.

The precooler is designed with an array of thin tubes through which the coolant (helium) flows, designed to maximise surface contact, and therefore heat transfer, while resisting the very high temperatures – up to 700°C in the tubes – and temperature gradients.

The core of the HTX is an array of 16,800 of these tiny tubes, arranged in a series of spirals within a 1-metre diameter cylindrical shape (see diagram). Each tube has just a 1-millimetre outer diameter with walls thinner than a human hair, manufactured from Inconel – a nickel-chromium-based super alloy, resistant to heat and creep. There are more than 39 kilometres of tubes, but their total mass is only 50 kilograms.

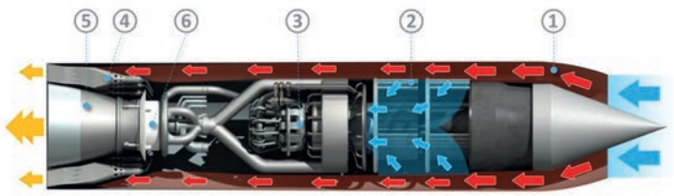
The air stream flows radially inwards through the precooler, while the helium coolant flows spirally outwards from the inner to the outer header. This counter-flow arrangement maximises the heat transfer rate while minimising pressure losses through the system

Air is a poor conductor, and the multitude of thin tubes maximises the cooling surface area relative to volume. The spiral arrangement of the tubes creates eddy shedding, which like the wake generated behind a bike or a truck, swirls the flow in behind the tubes, allowing the faster freestream flow to get closer to the surface and therefore transfer heat between the two more effectively.

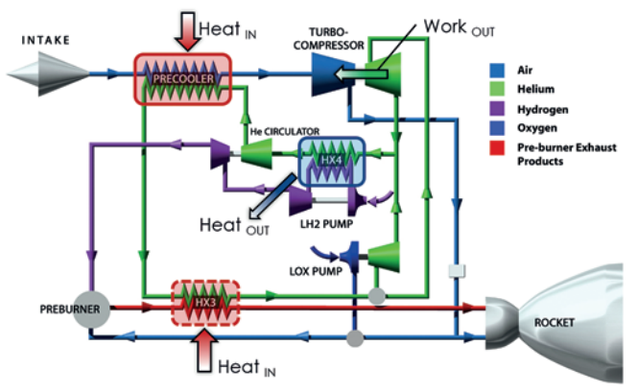
The tubes are pressurised with helium at over 200 bar during operation, and subject to temperatures of over 700°C. The key challenge for precooler construction was forming and joining these tiny tubes in Reaction Engines' assembly plant at Culham in Oxfordshire. This included creating leak-free joints at the ends of each tube, where the metal temperature in operation would be highest. The solution involved vacuum brazing several thousand joints simultaneously.

There was no obvious facility for testing this unique precooler, so – supported by the US Defence Advanced Research Projects Agency (DARPA) – the company built its own hot-air test facility in Denver, Colorado, and carried out a series of tests at increasing temperatures, culminating last October with a test to replicate performance at Mach 5. To supply the required air mass flow through the heat exchanger at the required temperature (1000°C), a donated General Electric J79 jet engine was mounted just outside the test building, to run at full power with maximum afterburner. The hot air was fed

THE SABRE ENGINE



1. High speed air entering the engine heats up as it decelerates to sub-sonic speeds (1,250 K at Mach 5)
2. The air precooler cools the high temperature intake air to near-constant compressor inlet conditions
3. The core engine compresses the airflow and rejects heat to the liquid hydrogen fuel via a closed helium circuit
4. The bypass burners and nozzles accelerate excess airflow to high velocity (fuelled by excess hydrogen from the core)
5. A common nozzle is employed for air-breathing and rocket modes of operation
6. A separate rocket engine is employed for exo-atmospheric flight from Mach 5 to orbital velocities



into the test unit and directed radially into the HTX before exiting outside. All elements including the test rig and ducting, the complex helium loop, and the instrumentation for measuring performance, had to be designed to withstand the effects of full test load, including substantial thermal movement. The hot helium also must be cooled before recirculating through the cooler. In the SABRE engine, this will be achieved in a heat exchanger with the liquid hydrogen fuel: for the precooler test, a large water boiler was used instead, rejecting heat as boiling water and superheated steam.

To everyone's delight (and, no doubt, relief), the test programme ran flawlessly.

Reaction Engines' test facility in Denver, Colorado, for testing the precooler up to 1,000°C. Heat was generated by the J79 jet engine running at full military power (left, with its exhaust plenum in the foreground). The hot air is diverted at right angles to feed the HTX in the shed behind © Reaction Engines

FUTURE APPLICATIONS

Meanwhile, development is progressing concurrently with the other major elements of SABRE, notably the air-breathing fuel-efficient core engine. The main objective is to demonstrate the operation of an air turbo-compressor driven by a close-cycle helium loop, with liquid hydrogen used as both a fuel and a heat-sink. Driving the air compressor from the helium cycle allows useful work to be extracted from the hot air, reducing the amount of cooling done by the hydrogen and removing the turbine from the exhaust stream (unlike a conventional jet engine), keeping thrust high and mass down, a key feature of the SABRE design. The successful precooler tests have already demonstrated that the air entering the turbo-compressor would always be at sea-level temperature and pressure. This simplified the design of the engine and avoided elaborate replication of hypersonic flight during testing. The test programme for the demonstrator core aims to begin in 2021.

Even if all goes to plan and funding is maintained, a SABRE vehicle in production is still probably at least a decade away, and meanwhile the company is exploring (with partners) other applications of its engine technology, particularly the precooler. This includes combining the precooler with a conventional jet engine – gas turbine, turbojet or turbofan – to improve performance. This could help produce faster jets, or more sustainable aviation. There is also potential for hybrid-electric propulsion. The precooler could also be used for improving power station efficiency and, in particular, for converting waste energy into renewable electricity. Reaction Engines is also looking at developing miniature versions of the precooler for Formula 1 and the high end of the automotive market is being investigated.

For some applications, taking the precooling down below ambient to cryogenic temperatures (-150°C) can potentially improve engine performance. But there are drawbacks, particularly the tendency for frozen water vapour to block the precooler. An ingenious methanol frost-control system was devised to prevent this and has already been successfully tested.

But perhaps the most exciting of the spin-off developments is the potential for hypersonic flight within the Earth's atmosphere. This opens up the possibility of commercial airliners capable of Mach 5 – a stated aim of one of the company's investors, Boeing – which could, for example, fly from London to New York in less than an hour. There is also clear potential for a new breed of hypersonic military aircraft, which has engaged both the UK's Ministry of Defence and DARPA in the US.

BIOGRAPHY

Dr Helen Webber is an Engineering Project Lead at Reaction Engines. She is responsible at system level for the engineering leadership and technical solution of the fully integrated SABRE Core Ground Demonstrator (aka DEMO-A).

LEARNING CODE WITH ROBOTS

A real, full-size robot dog that can hold a conversation, follow an ultrasonic 'whistle' and even has a socket to recharge your mobile phone

Richard Hopkins has built a full-size robotic dog out of inexpensive and easy-to-access technology. K9 can hold a conversation, move without a human controller and 'see' his surroundings. Richard explains how K9 works, and how he's using the robot to inspire the next generation of engineers.

Richard Hopkins built his career delivering major new information technology systems, mostly for the UK government. If you've been in the UK for the last 25 years, then there's a good chance you've used (or been processed) by one of his systems. The projects he leads are large and complex; back in 2011 he was appointed as an IBM Distinguished Engineer, an executive but technical role.

Five years ago, Richard started work on a full-size replica of *Doctor Who*'s robot dog, K9. His K9 is just like the one on the television; the only difference is that his is a real robot, not a BBC radio-controlled prop. K9 can wag his tail, hold a conversation and follow an ultrasonic transmitter. He even knows when he's been patted.

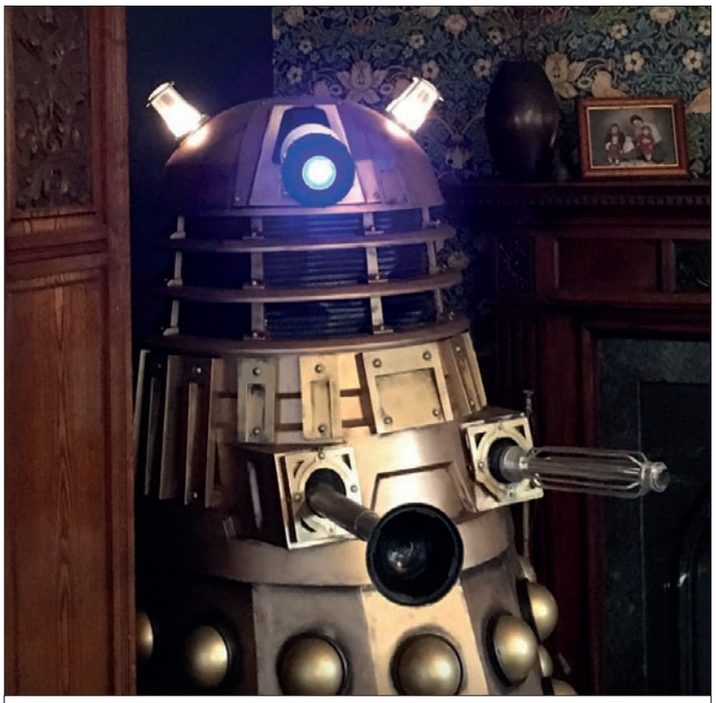
"K9's my long-term project to inspire kids, but he weighs as much as a big Labrador dog and I have to remove his tail to fit in my car! I pretty quickly realised I needed an easily portable version," said Richard. "My new one is a third of the size and only weighs the same as a Chihuahua. Just like the big one, you can have a conversation, but his special additional skill is that he can play grandmaster-level chess. He's called Kasperwoof."

Kasperwoof's name is a joke – he's a canine homage to Gary Kasparov the world chess champion who was famously beaten in 1999 by IBM's Deep Blue computer, the first computer to beat a reigning world chess champion. It is a sign of how far computers have come in that Richard claims that Kasperwoof would probably give Deep Blue a good match.

Richard has a self-imposed rule that all his robots must be made from inexpensive, commodity technology. His blog provides designs, code and explanations, and everything is published under an open source licence. He encourages students to inexpensively copy his inventions.

Why is this important? Older readers will probably remember IBM, but from the 1990s onwards, IBM slowly disappeared from public view. As it shut down its consumer-facing divisions – typewriters, then printers, PCs, and laptops and ceased to be as visible to everyday consumers. The company encourages its employees to work with schools and universities to inspire pupils to study STEM subjects and learn a little about the company.

Richard explains: "When I was in primary school, *Star Wars* was the thing and the robots R2D2 and C-3PO were stars. Back then, even *Doctor Who* had a robot dog. When I talk to kids today, nothing much has changed … artificial intelligence is a bit scary, but robots like BB-8 are still cool. So that's what I decided to do. I would build robots to inspire kids.



Dalek Fry, the doorman, works as an around-the-clock security guard

"As part of the STEM Ambassadors scheme, I visited a school where I met children in years four to six. I'd been warned by my wife, an ex-primary school teacher, that year six might be challenging and that nothing I'd be able to do would impress them. Not so. I knew I'd won them over when one of them asked 'And they pay you to do this? Are you a genius?' I would have grinned. 'Nope – just an engineer, still learning'. I'm now roughly the same age as their grandfathers, but they were almost in awe that I'm still being paid to have fun and learn new things. For a brief moment they grasped why engineering is so great. I hope that inspiration lasts."

NEW INNOVATIONS

Richard is convinced that his work has brought unexpected benefits, helping to transform some of his major system designs. IBM Distinguished Engineers deliver major new innovations or design and build challenging systems. Richard explains: "This continual focus and valuing of questioning and

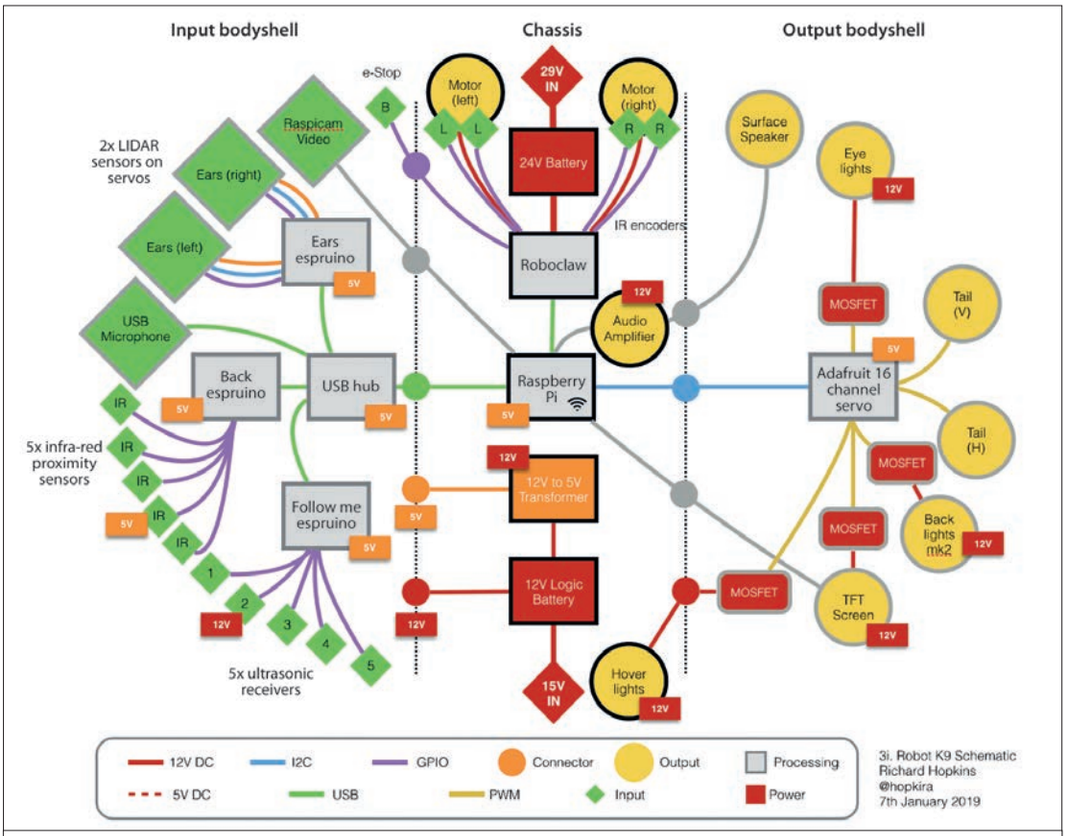
continued on page 26

HOW DOES K9 WORK?

K9's computer is a £32 Raspberry Pi 3B. His robot functions are written in a language called Python and his control user interface is written in JavaScript React (just like many commercial websites). The user interface allows someone online to see what he sees through a camera built into his eye panel, which provides a visualisation of his surroundings based on the information from his sensors. He can also be moved around using a touch sensitive joystick on an iPad. K9 has a microphone in his nose, a surface resonating speaker built into his head and a screen built into his side – all connected to the Pi.

K9 streams the sound from his microphone over the internet to IBM Watson Speech to Text Cloud service; a written version of what he has heard is then returned to him via the same stream. He uses the free tier of IBM Watson Assistant to respond to what he has heard. Watson Assistant works out the likely 'intent' of the command that K9 has been given and then choses from a variety of responses. For example, K9 identifies phrases such as "Good boy K9" or "Would you like a jelly baby?" as the 'praise' intent. His response will be to wag his tail and respond: "Thanks are not necessary". His side-screen displays a dashboard that describes the state of his batteries, his speed and his power consumption.

Not bumping into things is important for any robot. To stop this from happening, K9 has 12 sensors (to avoid collisions) and four servo motors (two to move the tail, two to turn the ears). Controlling all of this via a Raspberry Pi would quickly overwhelm it, so he has three

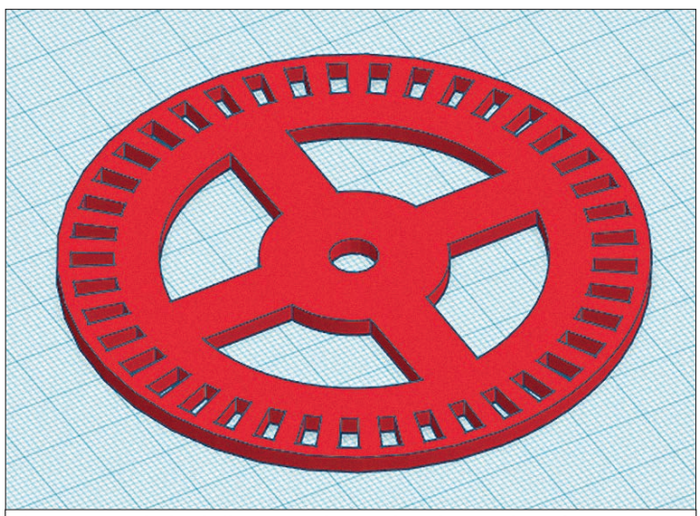


This shows how K9 is put together with a Raspberry Pi at the centre

microcontrollers that do this for the Pi. These microcontrollers (called Espruinos) convert the signals coming from the sensors into information that the Pi can easily process. For example one microcontroller moves the ears forwards and backwards. While it does this, it measures the voltage signals from the LIDAR (which tells it how far it is to an obstacle) and the signal from the potentiometer in the servo (which tells it which direction the ear is facing). It then translates those signals into vectors to the nearest obstacle. These microcontrollers use USB to send the vector data to the Pi as simple strings. This 'pre-processing' offloads work from the Pi and gives it enough time to make decisions (such as whether it is safe to move forward or not).

Making him look alive is done by giving him movement and lots of flashing lights. K9 has 12 flashing buttons on his control panel, a concealed blue LED strip around his base (which makes it look like he's hovering) and two 'eye' lights. The brightness of these lights is controlled by a very fast pulse 3.3V signal from a microcontroller. This signal is 'amplified' to 12V. If the high pulse signals are short, the light looks dim, if they are long the light is very bright. The faster K9 is moving, the brighter the blue lights underneath him glow.

K9 is quite complex. To enable information to flow around the robot so that he can make sensible decisions, Richard uses two key programs. The first is



This 3D printed wheel allows K9 to know where he is within a few millimeters

HOW DOES K9 WORK? CONTINUED

Node-RED, which is a free tool that enables the user to wire together hardware devices via visual flows without doing any programming (like a sophisticated version of Scratch). Nearly all the sensor data that flows around K9 is fed into Node-RED so it can be routed to the right program. The second program, called Redis, is the main destination for much of the data – it is also free. Redis is usually used to help scale large websites, but Richard uses it as K9's short-term memory. Node-RED flows the data into Redis so that K9 can build up a picture or 'context' of his surroundings. This enables him to make decisions, such as how to navigate past an obstacle to get to where he's been asked to go. A Raspberry Pi is a relatively small computer, so remembering all this data would quickly fill it up; Redis automatically forgets what it saw as new data becomes available.

Moving precisely is very important for any robot. Unfortunately, powerful, precisely controllable motors are very expensive. Richard solved this problem by using two inexpensive scooter motors and gluing a 3D-printed disc to each. These discs have many holes around the edge. As each wheel turns, four sensors detect these holes. By counting the holes that pass the sensors, it is easy to calculate how far each wheel has travelled. Depending upon which sensor sees the hole first, it is also possible to work out which way the wheel is turning. Combining the signals from both wheels allows the robot to work out in which direction he is moving (and make adjustments to the power going to his motors if he not moving as expected). Richard's K9 is fast and can move in a straight line, or spin precisely on the spot without a human operator controlling him.

renewal has helped IBM to exist well beyond 100 years. But it's that questioning that keeps us innovating and inventing. Our challenge, of course, is staying up to date with fast-moving technologies."

Things he has learned from his robots and commodity technologies, especially cloud and AI, have helped IBM deliver new systems for clients. Richard recalls one episode "The 'hands-on' knowledge that I gained from building my robots meant that I had an in-depth understanding of how to automate the creation and testing of new systems on the cloud. That convinced the client that we were the right company to work with. On other occasions, simply being able to talk about the practical pros and cons of the latest technologies has made all the difference when co-creating solutions with the client's team."

Richard has also found that he pushes both himself and technical boundaries. For example, he says: "Imagine you want your robot to find you and you're holding an ultrasonic transmitter. Your robot dog has five ultrasonic sensors arranged around his body, which are creating a flood of raw sensor data. Unfortunately, the data is noisy, so you must perform an algorithm sequence on each to separate the signal from the noise. Those signals then have to go into a neural net so the robot can determine the bearing and distance for the transmitter, which will allow him to home in on you. It sounds simple, but imagine having to do that every few milliseconds on a £15 microprocessor. When you have powerful computers with GHz processors to play with, making every clock cycle count is a forgotten skill. Not for me, not anymore."

"Not many of my family or friends understand what I do as an IBM Distinguished Engineer, but my robots capture the essence of it and allow the kids to imagine what I do. Because of my 'commodity technology only' rule, budding engineers can follow my lead."

One of Richard's 'robot proteges' built his own K9 from cardboard that could answer basic questions. Now in college, he is working with IBM Researchers in Australia and New York on a project to engineer a companion robot for those with Alzheimer's.

Richard is currently working on a Dalek that acts as a doorman for his home. The Dalek works out who is in, or out, of the house using their mobile phones and then recognises faces so it can greet you or say goodbye. The lights and the iris of his eyestalk are all under computer control, so "when he 'wakes up' and talks he's pretty convincing. Of course, if he doesn't recognise you he threatens you with extermination. He's grown quite famous with our local delivery people."

**BBC, Doctor Who, Dalek and K9 (word marks, logos and devices) are trademarks of the British Broadcasting Corporation © BBC 2020. Daleks are copyright BBC/ Terry Nation. K9 is copyright Bob Baker/David Martin/BBC. Richard's robot designs are not used for commercial purposes.*

BIOGRAPHY

Richard Hopkins is an IBM Distinguished Engineer and a STEM Ambassador. He is currently the 19th President of IBM's global Academy of Technology. He lives in the North East. To find out more about his robot designs, visit his blog at https://k9-build.blogspot.com/ and for more information on code, visit https://github.com/hopkira

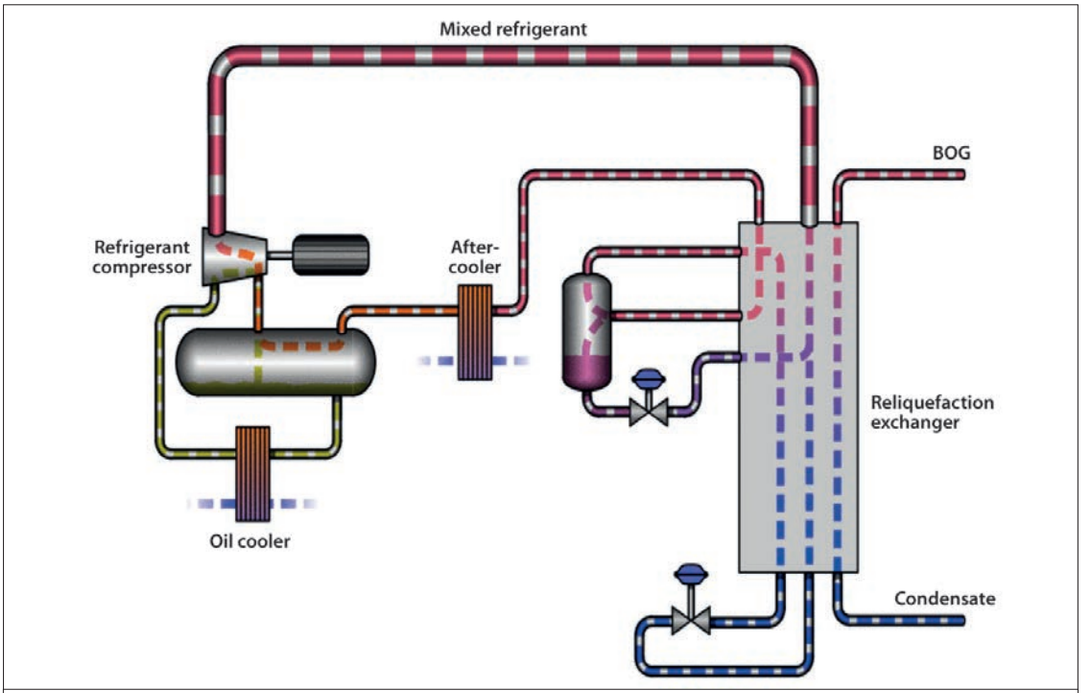
SUSTAINABLY TRANSPORTING GAS

Babcock LGE has developed truly disruptive technology for transporting liquefied natural gas. Its ecoSMRT® reliquefaction system reduces the carbon footprint by up to 50% and returns more than half the boil-off gas that would previously have been lost back into cargo storage. Dominic Joyeux asked the 2020 MacRobert Award finalist's team about its innovation.

LNG is natural gas condensed to a liquid by being cooled to -163°C. This process reduces the volume by a factor of more than 600: a single shipload containing 150,000 cubic metres of LNG equates to carrying 90 million cubic metres of natural gas © SovComFlot (SCF)

Boil-off gas is a problem that all tankers carrying liquefied natural gas (LNG) face. The temperature-controlled tanks on board ships cannot provide complete insulation against warming. The result is that some of the LNG evaporates, which produces the boil-off gas. The resulting gas has to be removed. Part of the boil-off gas can be used as fuel for the main engine and auxiliary generators, with the surplus being either burned in a gas combustion unit (GCU) or reliquefied.

In a typical 20-day voyage, about 2% of the total volume of the LNG cargo turns into boil-off gas. Thousands of tonnes of cargo are lost each year on LNG carriers without a reliquefaction plant onboard when cargo is burned in the GCU and, up until now, reliquefaction plants have had the complexity of an external precooling system and the energy needed to power it.



The ecoSMRT® module contains a closed loop recirculating system of a refrigerant mixture, which is compressed in an oil-injected screw compressor, cooled by freshwater, and fed into a multistream reliquefaction heat exchanger to generate the low temperature necessary to condense and precool the boil-off gas, which is then returned to the cargo tanks © LGE

Thanks to a small team of engineers based in Rosyth, things have changed. Their work has refined onboard reliquefaction that delivers a 40% reduction in the physical space required and huge environmental savings.

THE CONUNDRUM

Formed 50 years ago, Babcock's Liquid Gas Equipment (LGE) has always specialised in the transport of volatile liquids such as LNG and liquefied petroleum gas. The company was acquired by Babcock International in 2012 but still retains its own identity and engineering focus. It has been providing services and working with the world's largest shipbuilding company, Hyundai Heavy Industries, for many years. LGE set out to solve the engineering challenge of the excessive amount of boil-off gas being wasted.

After much discussion and commercial negotiation, Babcock provided the risk capital of £1 million for LGE to solve the problem. If successful, Hyundai Heavy Industries would have an exclusivity deal for two years. LGE retained the intellectual property since its conception with full rights to sell the technology to third parties. The deal was agreed, now the problem just had to be solved.

Transporting liquefied gas is an area with hundreds of patents. One of the key challenges was to come up with something different that didn't infringe on any other patent. The aim was to develop a modern efficient reliquefaction plant that was fully automatic and simple to operate.

BREAKTHROUGH IDEA

LGE aimed to improve on alternative technologies to re-liquefy boil-off gas, which had often used cumbersome, inefficient systems built and placed onboard ships. These used external or auxiliary cooling systems, such as secondary refrigeration setups that required an additional compressor – an energy-intensive complex piece of rotating machinery that took up space and used up power.

LGE took a fresh look at the overall design requirements and combined the heat loads and related functions into one heat exchanger. Using this as the heart of the design meant that only one piece of rotating equipment was required – the main refrigerant compressor.

This breakthrough concept led to the ecoSMRT®, a simpler and significantly more efficient design, both in terms of performance and size. By incorporating the precooling of the boil-off gas into the main heat exchanger (a bespoke plate-fin heat exchanger, where plates and finned chambers are used to transfer heat between fluids), there is no need for an additional compressor, cooler, or knock-out drum. It simplifies the process, removes weight, frees up space, and cuts out a whole raft of equipment.

The ecoSMRT® uses an oil-injected rotary screw compressor. Special attention was paid to the handling of oil carry over and a patent-pending bespoke design was developed to prevent oil carry over into the cryogenic section of the reliquefaction condenser. If this happened then the temperatures of -163°C would cause the oil to freeze and consequently the system to fail.

LGE tackled this challenge in two ways. The first was to

design the ecoSMRT® so that it incorporates an inverted U-bend in the piping around the heat exchanger. Simple but effective, this solution physically segregates thermodynamically equivalent oil-containing streams from the cryogenic parts of the heat exchanger. This eliminates the risk of contamination and subsequent operational problems.

The second solution was to select the most appropriate lubricant and prevent it from coming into contact with the cold sections of the primary heat exchanger. The team worked with Hydrafact, a gas hydrate specialist, to laboratory test a selection of lubricants and find a bespoke solution.

ITERATIVE PROCESS

One of the most impressive things about this project was that it only took three years from concept (2015) to first sale (2018). In the end, LGE went straight to production without a prototype. Everyone involved must have had enormous confidence in the design to build a multi-million pound unit that fits into a LNG tanker without making a full mock up model first, but the iterative engineering design process involving different disciplines created confidence in the undertaking.

LGE used innovative thinking, dynamic simulation, rigorous analysis, and continuous improvement practices to ensure that the skid design the engineers had chosen was as efficient and compact as possible. The team modelled every area and then went back to the different manufacturers they were working with. This proactive work over a short period enabled the team to resolve many problems.

The computer-aided engineering 3D model was used for the customary construction and operability reviews. In addition to this, a virtual-reality model that could be 'walked around' was also created. This supported early familiarisation of the layout, but also allowed the crews who will be operating the plant to have hands-on input to the layout.

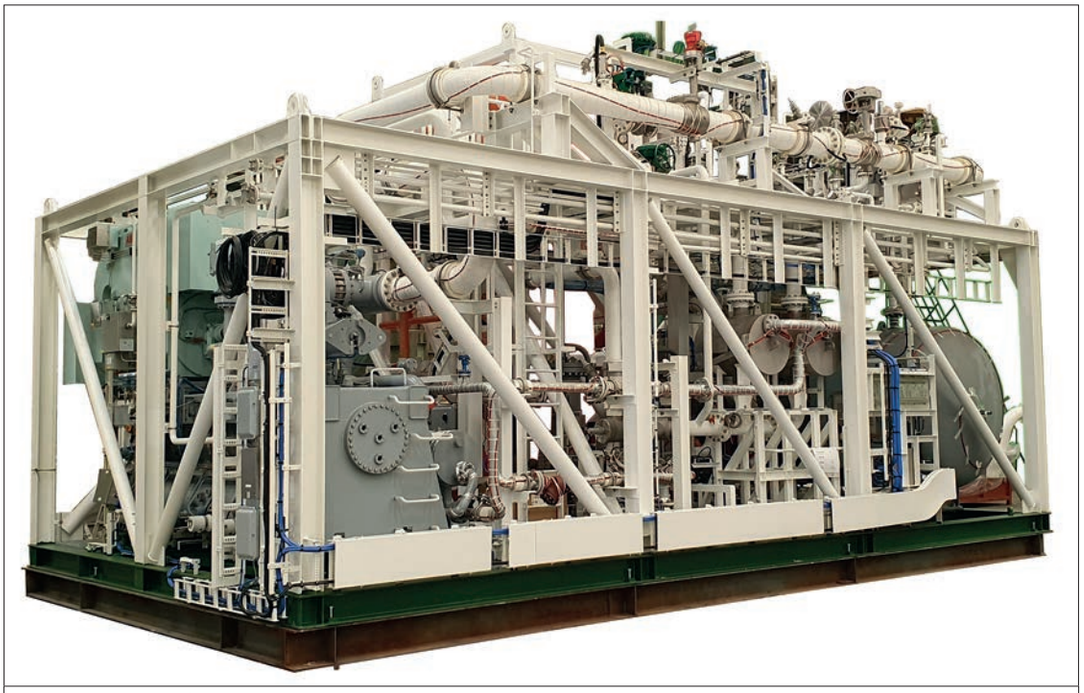
The inverted U-bend that helps separate out oil-containing streams from the cold parts of the heat-exchanger © LGE

For shipowners, ease of operation was a crucial factor. A gas chromatograph helps automate the system – the machine separates the mixtures and samples both the boil-off gas and mixed refrigerant streams to determine if the mixed refrigerant gas composition is optimised to the LNG. After sampling, the operator can add the required refrigerant gas to improve the performance of the plant via its integrated automation system.

The ecoSMRT® also takes up less space – it is 40% smaller than existing reliquefaction setups. The increased liquefaction rate and lower power consumption reduces through-life costs too. A 50% reduction in maintenance costs is achieved by halving the amount of rotating machinery onboard.

A VIABLE PRODUCT

The final ecoSMRT® skid measures 11.2 metres long by 5.5 metres wide by 6 metres tall – the dimensions can be tweaked for different ships when installed either as retrofits or as



The ecoSMRT® skid fully assembled – as delivered to shipyard © LGE

pre-builds. It is, in effect, a drop and plug-in system. The first sale was in 2018 and the first units are already crossing the oceans on LNG tankers.

Feedback from the commissioning, gas trials and early operation of the plants has been taken back into a review of the design but the real-world functioning of the system is mostly as forecast. The vibration design had been thorough and had anticipated all possibilities. A large tanker being buffeted by sea waves will encounter a lot of pitching and rolling: the engine will shake and the propellers will churn. The steel frame of the module and all the piping and equipment in it will feel all these vibrations, as well as the buzzing of the refrigerant compressor. Tuning the skid for all these sea-going eventualities has proven to be a highly successful example of mechanical engineering.

This engineering impressed the MacRobert Award panel of judges, along with many other aspects of the innovation including its commercial and environmental potential. In the first two years since product launch, 39 ecoSMRT® modules have been sold, with 34 in production and five already in use. This represents achieving a 40% addressable world market share – a remarkable figure.

For ship-owners, the fact that 56% of the boil-off gas is captured and returned to the cargo tanks by ecoSMRT® is a major factor – with the remainder used to fuel the main engine and auxiliary generators. Tankers that didn't have the additional reliquefaction options would typically use a third of the boil-off gas for engine fuel and lose nearly two-thirds by burning it off in the GCU. As well as the monetary gain this represents, it means that each such tanker will now stop an estimated 19,000 tonnes of CO_2 from being produced every year.

With demand for LNG set to double by 2040, boil-off gas recovery will be an important factor in improving the environmental credentials for carrier fleets. When all the ecoSMRT® systems currently being produced are operational, they could save nearly 750,000 tonnes of CO_2 emissions a year compared to no reliquefaction. With the industry's carbon footprint facing closer scrutiny from the International Maritime Organisation, this is an arresting and significant achievement.

LGE'S FINALIST TEAM INCLUDES:

Neale Campbell, Managing Director
Alan Duckett, Technical Director
Dr Nik Felbab, Principal Process Engineer
Anselm Foxell, Principal Mechanical Engineer
Anne Keron, Process and Safety Engineering Manager

The author would like to thank MacRobert Award judges Dr Liane Smith FREng and Gordon Masterton FREng FRSE for their help in the writing of this article.

Shadow Robot Company's advanced robot hand is able to transmit touch sensations across rooms – and across countries

HANDS AS MACHINES

Robotic hands are designed to serve one of two separate purposes: as prosthetic devices acting as the functional replacement for a missing natural hand; or as machines for manipulating objects in the manner of human hands. Focusing on the latter, Geoff Watts spoke to Rich Walker, Managing Director of Shadow Robot Company, about the mechanical hands that are doing the tasks human hands cannot.

To watch one of these versatile hands unscrewing a bottle top, picking up an egg, or removing a credit card from a wallet is to witness something obviously mechanical, but uncannily familiar

As a device for seizing, holding and manipulating objects of all manner of shapes and sizes and with varying degrees of fragility, the human hand is almost unrivalled. Recent years have witnessed the birth of a mechanical challenger. Called the Dexterous Hand, its parent is the Shadow Robot Company, based in Gospel Oak, London. To watch one of these versatile hands unscrewing a bottle top, picking up an egg, or removing a credit card from a wallet is to witness something obviously mechanical, but uncannily familiar.

Entertaining, of course, but there is more to these robotic hands than the performance of party tricks. Set up as a company in 1997, Shadow sold its first robotic hand some three years later. An early customer was the Neuroinformatics Group at Bielefeld University in Germany. The university found that the hand's human-like design served as the perfect test bed to devise, evaluate and improve the computational models of human manual intelligence on which they work. They have been buying the mechanical hands ever since.

Although many of Shadow Robot's current customers are academics or otherwise involved in R&D, the company's managing director Rich Walker foresees the sale of more and more hands intended not only to develop new ways of doing things, but actually to do them. Suppose the task to be carried out is in a toxic environment, or one that has to be sterile, or one contaminated by noxious fumes or otherwise too risky to allow the presence of a human. Suppose it involves dismantling a bomb, or working in deep space, or experimenting on lethal microbes. Or suppose the environment is safe but the person on whose behalf the robotic hands are acting is incapacitated.

In the pharmaceutical industry, for example, many of the tasks carried out by staff working in sterile areas are quite menial: taking a Petri dish and spreading a sample to be cultured across the growth media in it; or moving trays from one part of the lab to another. Although many such tasks have been automated, some still require the intervention of human hands – and training humans to maintain sterile conditions is hugely time consuming.

Shadow is also talking to people in the nuclear industry in the UK and Japan, not so much in connection with heavy engineering tasks but for analytics labs where staff are often working with radioactive and otherwise contaminated and toxic materials.

LENDING A HAND

The principle underpinning the design of the current generation of Dexterous Hands is precisely what it was at the outset: a close copy of the human hand – in size, shape, overall appearance and function. The materials that it is fabricated from – aluminium, steel, delrin, polycarbonate, and polyurethane 'flesh' – are of course non-biological, but otherwise the differences are

SHADOW'S ORIGINS

Rich Walker, Managing Director of the Shadow Robot Company, describes himself as having been "a geeky kid who liked playing with computers". During a computing activity holiday in his late teens he met Richard Greenhill, a multitalented inventor who, with some like-minded enthusiasts, had built a bipedal robot. Walker got involved with the still informal group; it flourished and even won an award at the Robot Olympics.

In 1997, the group was approached by a company who wanted to buy some prototype actuators from them. To facilitate this, they turned themselves into a company. This allowed them to seek finance for what they were doing, including a Smart Award from the then UK Department of Trade and Industry. What had started as a hobby became a business. The Shadow Robot Company was up and, if not exactly running, certainly walking. It now employs more than 40 people and is one of the longest established robotics companies in the UK. It has collaborated with a variety of British and overseas organisations including GSK, Siemens, NASA and MIT. The prototype of its original walking robot is now in the Science Museum's permanent collection.

Over the past five or six years the company has been growing at a rate of more than 20% annually but not as the consequence of a plan. It has simply happened: grown organically you might say. Walker is content with this, declaring himself less concerned with the growth of the company than with ensuring that it remains one in which employees enjoy producing a product that they and their customers have a high regard for.

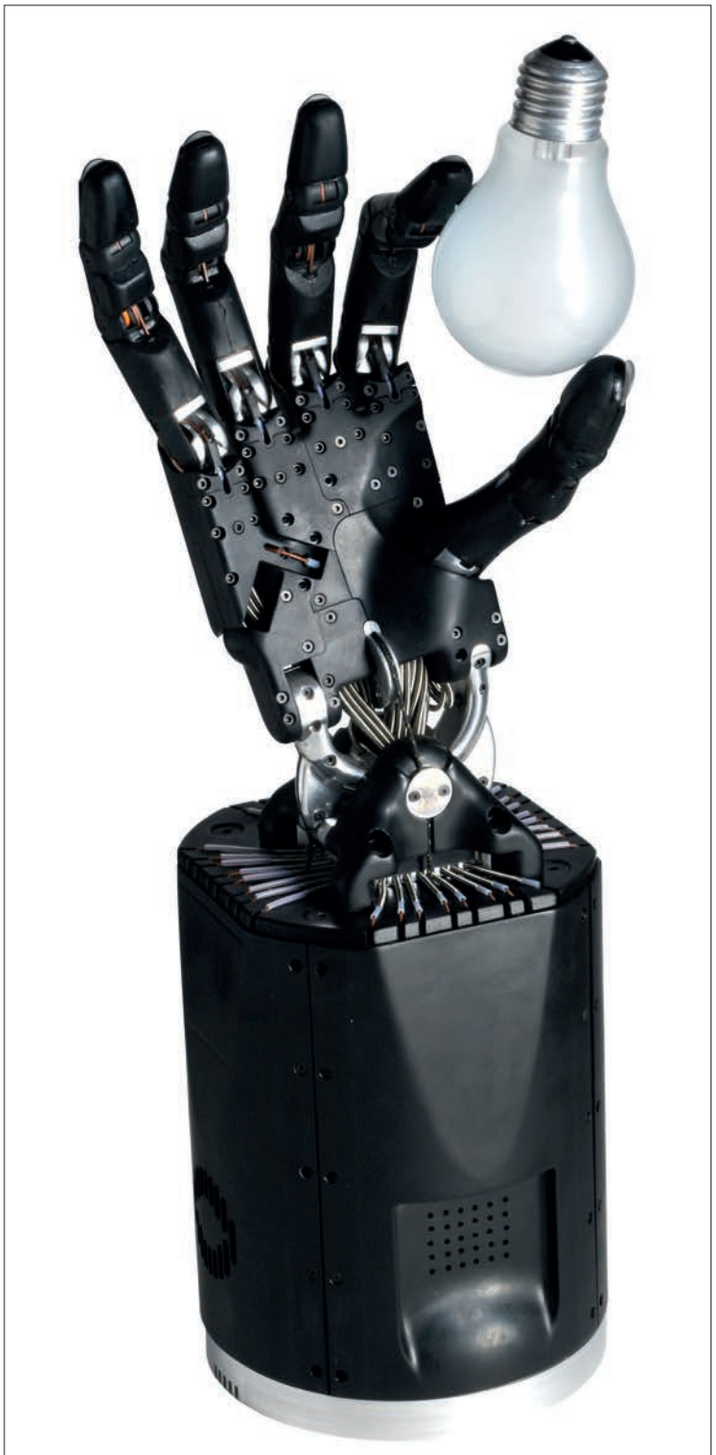
minor. The robot hand doesn't, for example, imitate some of the more complex movements of the thumb. It could have been designed to do so, but Walker and colleagues felt that the gains would not justify the effort. Likewise with the movement of the outermost joint of the fingers. Some of us can move this independently of the penultimate joint; but for most of us, and for most purposes, movements of the two outermost finger segments tend to be coupled. And so they are in the Dexterous Hand. However, in all other respects anything your hand can do, so can the Dexterous Hand.

The Dexterous Hand has 24 joints driven by 20 individual motors; the difference in number reflecting the already mentioned decision to allow movements of the outermost finger joint to be actuated by those of the joint proximal to it. The 20 motors and their associated gearing are located in the 'forearm': the circular base on which the hand is mounted. The motors are linked to the joints and actuate them by cables; they can generate forces comparable to those of a human hand. The fingers have three degrees of freedom while the thumb has four. The hand and forearm together weigh 4.3 kilograms and can hold objects as heavy as 5 kilograms.

The Dexterous Hand can sense the force it is applying to whatever it grips by pressure sensors built into the surface of each figure tip. Extension of the sensing system to other areas of the hand is still a work in progress, but data on finger pressure alone is more than adequate for achieving and controlling most of the tasks it can undertake. The pressure being applied by the finger can also be inferred from strain gauge measurements of the tension in the cables that actuate joint movements.

Hand movements can be pre-programmed if the task to be performed is routine and repetitive. But more commonly the control system relies on signals from an operator wearing a motion-tracking glove. When Shadow began operating, the choice of such gloves was limited, but in recent years the technology has significantly improved.

To make practical use of the actions of a robotic hand it will usually need to be attached to some other piece of machinery, typically a robotic arm. Integrating the two sets of software and systems is not



The Dexterous Hand has joints similar to a human hand and has pressure sensors built into the fingertips so that it can sense the force it is applying to objects

The Shadow Dexterous Hand with tactile sensors is controlled by a haptic glove allowing the operator to 'feel' what the robot hand is touching

usually a problem, especially for other equipment that uses the Robot Operating System (ROS), an open-source set of software libraries and tools that Shadow has been using for the past 15 years. During that time, according to Walker, manufacturers of equipment like robot arms have become increasingly aware of the value of compatibility with the products of other companies.

ROBOTICS IN REAL LIFE

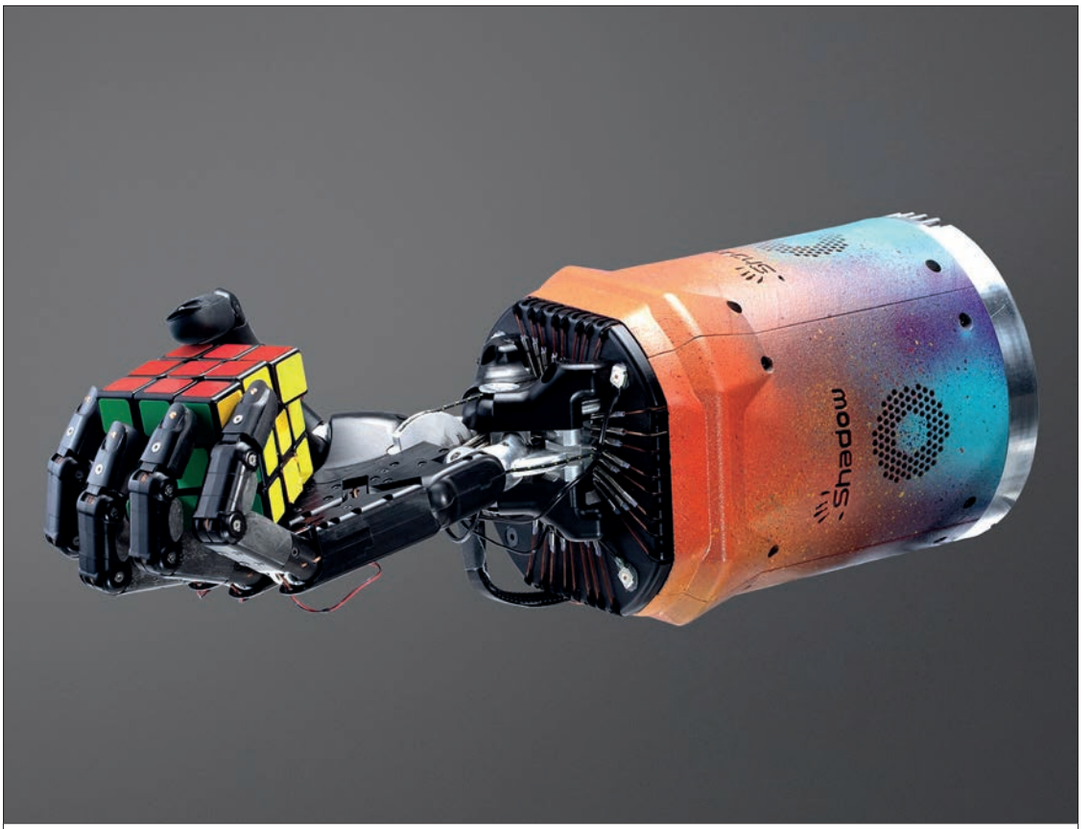
An idea of what the future might hold can be gleaned from a 2019 demonstration that Shadow set up in collaboration with two Californian companies: SynTouch that specialises in manufacturing tactile sensors and HaptX, which makes haptic feedback gloves. An operator in California wearing a haptic glove used it to control an arm-mounted Dexterous Hand typing on a keyboard in London. As the tactile sensors on the robot's fingertips responded to the press of each key, haptic data travelled over a network back to the human operator in California who, 5,000 miles away, could feel the pressure in real time that he (or rather the robot) was applying to the keys.

Walker's company is piloting this approach to robotic control for a major engineering company. A system of this kind would allow a centrally based engineer to deal with critical equipment that needed immediate attention but was remotely located and difficult to reach. Robotic hands could save costly time.

Future robots should also be able to reap the benefits of machine learning, another aspiration that has been explored using the Dexterous Hand. In this case Shadow partnered with a third Californian company, Open AI. It is possible to build machines that, like humans, can learn by experience. But to perform an intricate physical task for real, and learn from mistakes, is slow and time consuming. Open AI has speeded things up by using computerised simulations of the task from which the system can devise effective finger movement patterns and strategies. When confronted with the real-life task, the computer controlling the robotic hand employs these strategies to ensure that it can achieve its goal promptly and efficiently.

The task that Open AI chose for this demonstration – the use of a robotic hand to manipulate objects in a purposeful manner – presents a major challenge; but Open AI's Dactyl system rose to it. Holding a cube, each face of which was clearly marked with a letter, the robotic hand's task was to manoeuvre the cube into a succession of chosen orientations. In front

Holding a cube, each face of which was clearly marked with a letter, the robotic hand's task was to manoeuvre the cube into a succession of chosen orientations



Artificial intelligence research company Open AI uses the Shadow Dexterous Hand to advance research in machine learning and artificial intelligence

of the hand, and viewing both it and the cube from differing angles, were three cameras. Using continual updates on the coordinates of the fingertips and the orientation of the cube, the hand carried out the necessary manipulations. Armed with the knowledge of the previous simulations of the task, it performed with impressive speed and total proficiency.

Despite repeated enquiries about what might appear to be the most obvious application of a robotic hand – as a prosthetic substitute for the real thing – this use is not on the Shadow agenda. The goals, problems and constraints involved in building a prosthetic hand are quite different from those addressed by the Dexterous Hand, Walker points out. And, as he adds, there are other companies that specialise in this endeavour.

Outside of the factory and the warehouse, robots have yet to make a deep impression on our everyday lives. The advent of domestic robots would, of course, change all that. The potential is clearly vast but so far largely untapped, not least because the tasks to be done around the home, while mostly basic, are so varied and often so fiddly. To imagine an all-purpose robot that might be able to tackle them is surely to imagine a robot with hands. To reboot an old advertising slogan, the future's bright, the future's manual.

WHY HANDS?

In part, Walker claims, the decision to specialise in hands was for the pure satisfaction of trying to meet a major challenge. To build a functional hand was a goal that no-one had fully and successfully achieved. More practically, Walker and colleagues reasoned that if robots were ever to become fully operational in the complexity of the real world, they would need something comparable to a human hand by which to interact with it. And, if comparable to a human hand, why not a simulation of the hand itself, anatomically and functionally? Engineering has a long and productive history of looking at nature's solutions to problems, and then imitating them.

BIOGRAPHY

Rich Walker is Managing Director of Shadow Robot Company. He has worked in robotics for over 20 years and sits on Innovate UK's Robotics and Autonomous Systems SIG Advisory Board. Rich is also a Director of euRobotics, an international non-profit association for all stakeholders in European robotics.

SILVER MEDALS

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

DR MARKO BACIC, ENGINEERING ASSOCIATE FELLOW, ROLLS-ROYCE

Dr Marko Bacic's engineering innovations have ensured engine safety and reduced the carbon footprint of Rolls-Royce aero engines.

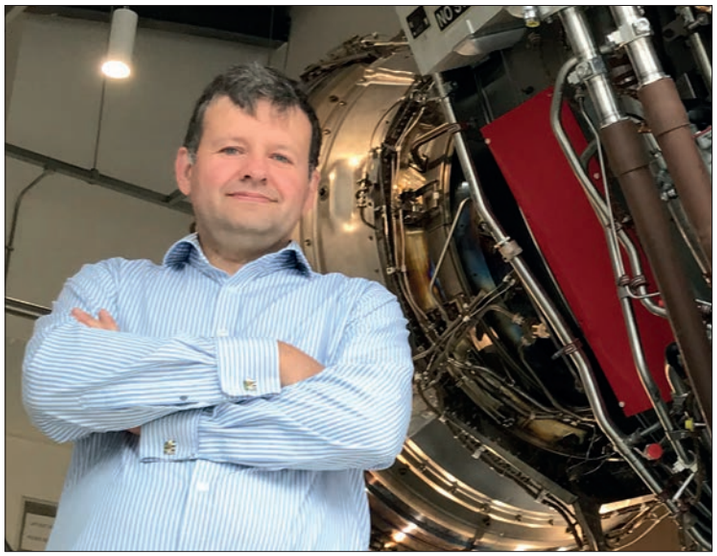
As a senior engineering specialist at Rolls-Royce and a member of the Faculty of Engineering Science at the University of Oxford, Dr Bacic can combine the real-world challenges he encounters at Rolls-Royce with the advantages of leading a research group at Oxford.

In 2011 Dr Bacic invented and developed a system to detect and safely address the very rare event of an engine shaft break, following analysis of an uncontained engine failure incident.

Dr Bacic's Model Based Detection System enabled Rolls-Royce to certify and ensure the continued airworthiness of all its latest Trent engines, which power over 40% of the world's modern large passenger aircraft fleet.

A prolific inventor, Dr Bacic has made major technical contributions to several novel carbon-reducing intelligent systems on Trent 1000, Trent XWB and Trent 7000 engines. These systems modulate air throughout flight in key parts of the engine, minimising fuel burn while maintaining engine life, and accounting for over £100 million of fuel and engine life fleet savings.

Along with driving the development of the next generation of intelligent systems for future Rolls-Royce gas turbines, Dr Bacic is working on technologies that will underpin sustainable aviation and transformative flight concepts, such as electric vertical take-off and landing aircraft.



MICHAEL BRONSTEIN, HEAD OF GRAPH LEARNING RESEARCH, TWITTER, AND PROFESSOR, IMPERIAL COLLEGE LONDON

Michael Bronstein has developed pioneering methods of graph deep learning: new artificially intelligent algorithms that perform machine learning on complex interactions such as molecules, biological interactions, and social networks. Graph deep-learning models have been successfully applied to a broad range of fields, from particle physics to drug development and the detection of 'fake news'.

With his collaborators, Michael developed a novel system for accurate and fast prediction of interactions between protein molecules, allowing the design of new proteins with desired properties. This research potentially paves a new way to design biological drugs against cancer.

With his students, Michael founded Fabula AI, a startup that commercialised his graph-learning technology to detect misinformation, or 'fake news', on social media. Instead of following the traditional approach of analysing the news content, Fabula AI used graph machine learning to analyse the news spreading patterns. The technology could accurately detect fake news within just a few hours of propagation. Fabula AI was acquired by Twitter in 2019.

ESTHER RODRIGUEZ-VILLEGAS, PROFESSOR OF LOW POWER ELECTRONICS, IMPERIAL COLLEGE LONDON

Esther Rodriguez-Villegas has created wearable devices to diagnose and manage respiratory conditions using pioneering low-power integrated circuit design. Her ultra-low-power circuits have also been used in miniature brain monitoring systems to improve the welfare of animals in medical research.

Esther's breakthroughs in low-power circuits have enabled her to create networks for highly accurate monitoring of physiological signals. Esther has modelled the physiological processes behind diseases, the type of user and the environment, with a focus on respiratory and brain conditions. Her aim was to create wearable devices that not only monitored medical conditions but had integrated diagnostic processing.

Esther founded medical device company Acurable to market her technology. The AcuPebble sensor is the first wearable medical device that can accurately diagnose and manage respiratory conditions at home. It records the patient's respiratory acoustic signals and then applies signal treatment algorithms to diagnose and manage conditions such as sleep apnoea, epilepsy, whooping cough, asthma and chronic obstructive pulmonary disease (COPD).

Its readings are seven times more accurate than current sleep apnoea solutions, with automated diagnosis and drastically reduced misdiagnosis. The device is non-invasive and can be used with no training, allowing home use without the assistance of a specialist or a visit to the hospital, which significantly lowers overall costs.

JAMIE SHOTTON, PARTNER DIRECTOR OF SCIENCE, MICROSOFT

Jamie Shotton was the leading engineer behind the machine learning that drives the human body motion capture system in Microsoft's Kinect, which won the Royal Academy of Engineering's MacRobert Award in 2011.

Using human motion capture to enable gesture-based user interfaces for computers and controller-free gaming on consoles had long been considered a near impossible task by many experts. Systems that required body markers to be worn existed, but human movement, the diversity of body shape and clothing, and the variety of home environments and lighting conditions meant that achieving it without wearing markers had remained an unsolved problem for decades.

After completing a PhD on visual recognition of objects from their shapes, Jamie saw that machine learning technology used for image classification could be repurposed as a radically different way to achieve human motion capture. The Kinect used this to become one of the earliest examples of large-scale machine learning and computer vision in a commercial product and was the fastest-selling consumer device ever at its launch.

Since then, Jamie has continued to work on computer vision and machine learning algorithms that understand people's motion and appearance for new applications. His team recently shipped the articulated hand tracking and eye gaze tracking on Microsoft's HoloLens 2, an augmented reality device. He is currently working on ways to transform communication through virtual 3D telepresence.

Dervilla Mitchell CBE FREng © Paul Carstairs

TEAMS THAT COUNT

For Dervilla Mitchell CBE FREng, a highlight of her time as a civil engineer has been creating teams of engineers and architects. More recently, Mitchell, a member of Arup's global Group Board, as Chair of the firm's UK, India, Middle East, and Africa Region, lead the region through a period of great uncertainty and disruption due to COVID-19. The recipient of the 2020 Royal Academy of Engineering President's Medal – awarded to a Fellow who has greatly contributed to the Academy's work and aims – Mitchell is also currently chairing a project on decarbonisation for the National Engineering Policy Centre.

Had Dervilla Mitchell CBE FREng followed her early interest, her career might have involved more earthly engineering pursuits than the airport projects and iconic buildings of her working life. "At university, my great passion was geotechnics – soil," she explains. Working on soil was unlike most projects thrown at engineering students. Soil was less straightforward. "Soil wasn't a homogeneous material," she says. "One had to try to understand it better."

When it came to finding a job after graduating with a degree in civil engineering from University College Dublin, the answer didn't lie in the soil. Arup offered Mitchell a job in structural design. "The idea of engineering, working in the built environment, was not in any way strange in my family," she adds. Her father was an architect, her grandfather and uncles were engineers. "Although nobody encouraged me into engineering, nobody discouraged me either. When I said I wanted to be an engineer, they said 'Very interesting Dervilla, carry on'. I chose civil engineering because that was closest to the built environment." An uncle also advised her to spend her summer holidays working, encouraging her to go to Arup during breaks from university.

For Mitchell, that first career move was the beginning of what she describes as a common theme in her working life. "Sometimes it is about taking the opportunities as they arise." Some people think of their careers as a linear path, she adds. In reality, it is a more undulating or circuitous path. "I could never have imagined when I started out that I would be sitting in London, being the recipient of the President's Award, being engaged with the Academy, attending the sort of meetings or doing the sort of projects that I do."

Mitchell highlights two other early influences in her career choice. As a schoolgirl, she visited her father's architectural practice. "I remember having seen people working in my dad's office as an architectural team. I absolutely knew from about 12 years old that I wanted to do something that involved a team." The second key influence Mitchell recalls was when a university lecturer, talking about concrete and materials, discussed practical issues and what to do with an education. "I could see then that it was the application of knowledge, and that learning, that was important, not the knowledge itself."

Mitchell's first job was in Arup's Dublin office. After four years, her husband, who she met at the firm, had an opportunity to study in the US. The couple moved to Massachusetts where she worked as a structural engineer on office and hotel developments for Weidlinger Associates. In 1986, they returned to the UK and Mitchell moved to Arup's London offices.

Mitchell has taken on progressively senior roles at Arup, working on projects of increasing size and complexity. Her career has included iconic civil engineering projects, from landmark buildings such as Portcullis House in Westminster to several airport projects, including Terminal 2 in her home city of Dublin and Terminal 5 at Heathrow.

While Mitchell has chalked up a roster of enjoyable projects (see 'Built on relationships'), one stands out, Terminal 5. It wasn't just the size of this £4 billion development at Heathrow Airport that appealed to Mitchell, but her role on the project. "I had to make a big step to go and take that on. I left Arup in central London and based myself at a co-located office at Heathrow for six years." It was also the opportunity to develop her belief in working with teams. Mitchell led an Arup team that, at its peak, had 60 staff based at Heathrow and 300 across the UK.

The teamwork at Heathrow extended beyond Arup. "Whether it was at Terminal 5 or later, when I went back to do the expansion at Heathrow, we worked in

BUILT ON RELATIONSHIPS

Clients arrive at engineering practices like Arup with projects of all sizes and shapes, from major airports to bus shelters. In her career Dervilla Mitchell has encountered many projects. The teamwork that develops between architects and engineers sticks out as a theme in projects that she remembers as being particularly enjoyable.

For Mitchell, Heathrow's Terminal 5 is her favourite project. However, she has fond memories of earlier projects. For example, Mitchell managed the development of a new paddock area at Goodwood racecourse in West Sussex. Arup had previously worked on the masterplan for Goodwood and the new project involved working with the owner of the racecourse. "I felt that it was a very personal project for them. It was their investment in the future of their very traditional racecourse: to make it fit and ready and exciting for the future." The delight, says Mitchell, is working with clients to produce something that they are really pleased about.

It also helps when you are working with architects who actively seek engineering advice. At Goodwood, the architect was Michael Hopkins and Partners, who she also worked with on another favourite project, the development of Portcullis House, the Westminster offices for Parliament. "I liked working with [Hopkins]. They were extremely demanding of the engineers in terms of producing a pleasing design but the engineering was always visible – the collaboration of the engineering and the architecture was really very critical."

Mitchell enjoyed working with the Richard Rogers architect's practice behind Terminal 5. "Both of those practices wanted to understand the engineering, they wanted to understand the rationale, therefore there was a close and curious and understanding relationship between architects and engineers."

Projects that Mitchell has worked on include Heathrow Airport's Terminal 5 (left) and Goodwood Racecourse (right) © David J Osborn/Graham Gaunt

integrated design teams: collaborating with other companies, listening to different disciplines' ideas, being open to new ideas. I found that very exciting. I think that enables us to get to better solutions."

Terminal 5 was also Mitchell's opportunity to master the management of diverse specialisms across a large-scale programme "Why was the roof a single span?" she explains. "Why was that connection designed like that? Why was the layout of the building the way it was? I felt that I knew pretty much everything."

Her job was to take a holistic view, understanding the client's needs while maintaining technical day-to-day communications with the Arup team and project collaborators. "That is a key moment in any person's career. It was also a very important time in my personal development, in my growth in terms of moving into leadership, being visible." Terminal 5 was of course was a very visible public project.

INCLUSION

That visibility has also taken Mitchell into the wider world of engineering. For example, at the Royal Academy of Engineering, she chaired the Academy's Diversity and Inclusion Committee for three years. For Mitchell, this area of concern almost crept up on her. "In my first job," she explains, "I never even noticed that I was the only woman for a long time. I was well looked after, nurtured, developed by those who I worked with."

Mitchell decided to get involved when she realised how few women there were in her industry. "I did work hard to champion getting more women into the industry and maintaining women who were already in and giving them satisfying and rewarding careers." Her engagement and approach began to change after she concluded she could do more than just ask challenging questions. "It was for me to step forward and make a difference for others." Being more visible in her diversity and inclusion work, both inside Arup, with the Academy and beyond, has positioned Mitchell as a role model for other women.

What started as concern for women in engineering has moved on to wider concern about diversity and inclusion. "Diversity is about the numbers and metrics, while inclusion is about the individual feeling welcome, feeling that they have a voice and that they have meaningful roles and careers."

Here the conversation is about race, disability, gender, sexuality, and neurodiversity, which encompasses dyslexia, autism and other hidden ways in which people can feel excluded. "I am an advocate of inclusion as the banner under which we have a lot of work to do across a range of dimensions of diversity," says Mitchell. As well as playing a leading role in the Academy's work on diversity, she also brings her determination to promote diversity, equality and inclusion to her work as a member of Arup's Group Board.

Diversity is more than just doing right by staff; it is also important for employers. As Mitchell said recently: "If you have a wide range of skills and a wide range of perspectives, you're much more likely to develop successful solutions that meet the needs of customers." She adds "When you have a diverse team and they are working collaboratively, constructively, listening to one another, and engaging with each other, it does lead to successful outcomes. And that is what we are really after."

NET ZERO

Mitchell accepted an invitation to chair a project on decarbonisation for the National Engineering Policy Centre (NEPC) – led by the Royal Academy of Engineering – which aims to look at some of the engineering challenges in the UK's stated ambition of reaching net zero carbon emissions by 2050.

Mitchell sees it as a part of her mission as an engineer to inspire and educate students about a career in engineering and construction. As a school governor she has inspired girls to pursue engineering careers. Within Arup she encourages and personally supports work experience placements for school and university students

"I did not consider myself to be an expert in the field of climate change, sustainable development, net zero or anything like that," Mitchell admits. "I did question whether I had the skills and understanding to really deliver change." She agreed to take on the task because she concluded that, as a neutral party, she had no vested interest in promoting any particular technology or form of energy.

Mitchell has set herself goals for her work with the NEPC. One issue she wants to tackle is increasing individual awareness of the urgent need for change. She also wants to encourage wider understanding of the topic within the engineering community and, in her own domain, the construction industry. "It is an extraordinarily complex challenge for us all." One task is to work out how the NEPC can influence policy and support government departments.

An important lesson is that there is no point in demonising the fossil fuels industry. The oil and gas giants may have risen on the back of carbon emissions, but they are well placed to move energy production to the next stage. "In transforming their business, they will make a significant contribution in this area," says Mitchell. They not only have the financial means but the knowledge and experience to make a significant contribution in attempts to deliver net zero.

In civil engineering, there have been signs of progress for some time. As an example, she points to airport projects she has worked on, which long ago ceased the energy-wasteful practice of running empty escalators all the time. More recently she has seen clients taking more imaginative approaches to climate change, such as reusing buildings rather than tearing them down and starting from scratch. She likens the pursuit of net zero to preparing somebody for the Olympic Games. "Every single little marginal gain had to be explored just to win the prize."

Mitchell's work for the NEPC is by no means her first foray into the wider policy arena. In 2014 she became member of the Council for Science and Technology (CST), whose role is to advise the Prime Minister on science and technology policy issues. Mitchell was one of the leaders of its work on harnessing technology to meet increasing care needs. She also led its 2018 work on *Computational Modelling: Technological Futures,* a topic that roared to prominence when its computer modelling hit the headlines during the COVID-19 pandemic. Mitchell describes the CST as "probably the most intellectually challenging and rewarding experience. You have to really think at a national level and outside of your own experience."

PANDEMIC RESPONSE

In both her public work and her position at Arup, Mitchell now finds herself thinking increasingly about the longer-term future. Net zero and COVID-19 are watersheds that upset the incremental, business-as-usual way of thinking. They are changing how engineers approach their work.

Take the global pandemic. As leader of Arup's UK, India, Middle East, and Africa (UKIMEA) region Mitchell was responsible for keeping the firm's UKIMEA offices up and running while "we all went into lockdown very suddenly". She explains: "Yet when it happened, with a bit of an investment in technology, we enabled 100% of our workforce be working away from the office." This meant ensuring that over 6,000 people across 23 offices in the UK, India, Middle East, and South Africa could work remotely pretty much immediately, changing how Arup thinks about how the firm operates. "Effectively, we are not rushing back to the office," she adds.

As a practice, that has a lot to do with creating the places where people work, Arup's clients have naturally called on the firm for help in their own responses to the global pandemic. "We did a lot of work for airports across the world, looking at what social distancing would mean to them. How might they manage passengers with the restrictions?" The firm's engineers are also experts in heating, ventilation and air conditioning (HVAC) and have done a lot of work on air transmission in buildings and how HVAC systems can be used to minimise the likely transmission of disease within offices.

More broadly, transport, another of Mitchell's professional interests, may be very different in a post-pandemic era. One beneficiary could be cycling, something of

Mitchell (right) with Arup's 2019 Top 50 Women in Engineering winners. In 2019, the award recognised exceptional apprentices; Mitchell won the award herself in 2016 and now encourages staff to enter

a passion for Mitchell who cycles into the office from her home in London. Before we have a vaccine and people are comfortable to cram onto crowded buses and trains, we are going to have to consider broader means of transport. "You can't encourage cycling just by saying it. You must make sure that the infrastructure to enable it is in place, or it won't happen in a safe way."

Transport and mobility is a good example of systems thinking, one of Mitchell's pet topics. With transport it would be far too easy to consider systems for trains, buses and cars as separate entities on their separate tracks. The real benefits come in tying them all together as a system of systems. The London commuter, for example, needs information on the whole transport system before they can decide what to do when, for example, the tube system is disrupted. "Ultimately, if we can feed real-time information into a system to pick up on our phones, that will give the public choice and it must deliver a more efficient system. That is a system of systems.

"I am very keen on thinking about this approach and systems of systems. It helps one understand the totality rather than just an element. It helps to understand the interactions between one's decisions." This approach brings many benefits. "If you're making decisions on something, how do you understand the unintended consequences?" Look at the systems level, she urges. Evaluate solutions for scenarios and you are in a better position to take the right decision or, as she puts it, the least wrong decision.

Mitchell's 'future thinking' comes with different time horizons. The most immediate challenge will be to see how engineers can help society to navigate the next two or three post-pandemic years, before vaccination can restore some sense of normality. Beyond that, it may be a few decades before the UK's 2050 target for net zero emissions is reached, but for that to happen engineers must work hard now. On another medium- to long-term horizon, Mitchell is thinking about another hot topic in policy circles. "How can science and technology contribute to the levelling up agenda?" Mitchell asks. Tackling that challenge alongside net zero will provide plenty of opportunities for teamwork and systems thinking not to mention attention to diversity and inclusion.

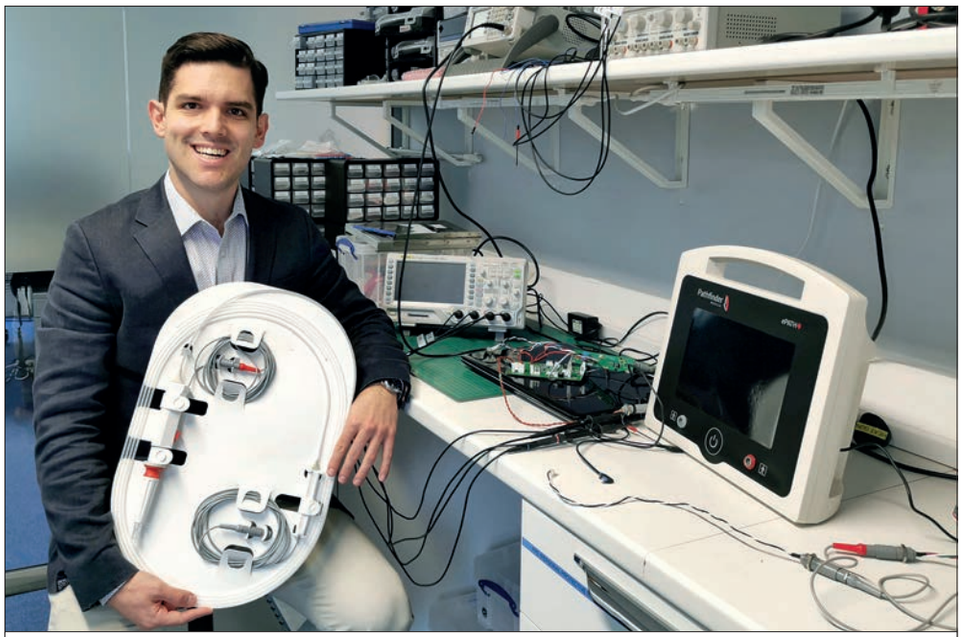
BIOGRAPHY
Michael Kenward OBE has been a freelance writer since 1990 and is a member of the *Ingenia* Editorial Board. He is Editor-at-Large of *Science|Business*.

CAREER TIMELINE AND DISTINCTIONS

Studied civil engineering at University College Dublin, **1980**. Joined Arup Dublin, **1980**. Joined Weidlinger Associates, Massachusetts, **1984**. Joined Arup London, **1986**. Fellow of the Royal Academy of Engineering, **2007**. UKRC Woman of Outstanding Achievement Award for Leadership and Inspiration, **2011**. Chair of Royal Academy of Engineering Diversity and Inclusion Committee, **2011–2019**, Became a member UK Government Council for Science and Technology, **2014**. CBE for Services to Engineering, **2014**. Honorary Doctorate from University College Dublin, **2016**. Top 50 'Women in Engineering in the UK', Women's Engineering Society in conjunction with *Daily Telegraph*, **2016**. Received *Building* magazine's Woman of the Year award, **2017**. Fellow of the Irish Academy of Engineering, **2019**. *Financial Times* 100 influential women in UK engineering, **2019**. Received President's Medal, **2020**.

REDUCING SURGERIES FOR DIALYSIS PATIENTS

Pathfinder Medical has invented a minimally invasive catheter guidance technology that will improve clinical outcomes for patients across the globe.



Sorin Popa holding up Pathfinder Medical's regulatory approved ePATH catheter kit

Over 3.5 million people worldwide have kidney conditions that require their blood to be routinely artificially filtered. This haemodialysis treatment means that their circulatory system needs to be regularly connected to a dialysis machine. To enable this, patients currently undergo a surgical procedure to prepare their vessels by forming a fistula, which is a connection between an artery and a vein in their arm. Pathfinder Medical's electronic catheter guidance technology enables clinicians to connect these blood vessels in a much less invasive way.

Sorin Popa, Founder and CEO, studied electrical engineering before doing a master's in bioengineering at Imperial College London. During this master's, he learned of an unmet clinical need for a more reliable method for patients with kidney failure to receive dialysis. The technical challenge was how to safely enable clinicians to connect blood vessels together in a more reliable way and without requiring open surgery. Sorin applied his electrical engineering background and research experience to develop a completely new method based on electric field guidance that enables clinicians to precisely position catheters within blood vessels and connect them to form a fistula. This is a safe way for patients to receive haemodialysis and the same technology can also be used to bypass peripheral arterial blockages.

The ePATH procedure replaces the current surgical option to access the vascular system, which has a more than 50% failure rate and is carried out by creating a dissection near the wrist. The ePATH's electronic guidance system enables a clinician to cross between vessels that are quite far apart without open surgery. The catheter system can be used to connect blood vessels using a small covered tube known as a 'stent graft'. It can also be used to bypass blocked vessels for those with peripheral arterial disease, which affects over 200 million patients globally.

Current vascular access options for dialysis patients often block up, requiring repeated costly repair operations (costing $4.6 billion a year in the US). The ePATH procedure improves outcomes for patients by reducing stress, discomfort and the risk of vascular access problems. It also reduces costs for healthcare providers by improving the reliability of the access site and reducing the likelihood of costly repeat procedures.

In just five years, Pathfinder Medical has gone from a prototype to receiving CE Mark regulatory approval and gaining UK and US patents on the technology. The device has been clinically tested and has further clinical trials with the NHS planned.

Sorin won the Royal Academy of Engineering's ERA Foundation Award, becoming a member of the Enterprise Hub, a network for engineering entrepreneurs from across the UK. He recently won the Sir George Macfarlane Medal, presented to the overall winner of the RAEng Engineers Trust Young Engineer of the Year awards. It is awarded to a young engineer demonstrating excellence in the early stage of their career.

HOW DOES THAT WORK?

MQA

MQA technology captures and authenticates the sound of the original master recording in a file small enough to stream at high resolution, allowing listeners to feel that they are in the studio with the performer.

How we listen to music has transformed significantly over the years: now most of us can access songs whenever and wherever we want to listen to them. In general, downloaded audio or streaming services offer listeners standard, compressed files that weren't produced by the artist themselves but created by third parties from studio quality master digital files, often leading to inaccurate representations of the audio.

Launched in 2015, Master Quality Authenticated (MQA) digitally captures and stores original master recordings as files that are small and convenient enough to download or stream. It captures archives efficiently, distributes music with the highest possible sound quality and then optimises it for each playback device. This end-to-end system removes unintended artefacts of the technology employed in real-world recording, distribution and playback.

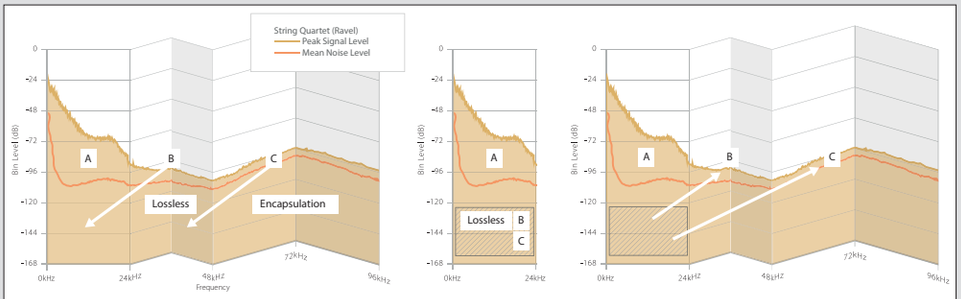
Although commonplace, converting audio to digital (and back) is imperfect and can limit sound quality. Conventional digital (PCM) is convenient for signal processing but inefficient for storing audio information. For example, lossless compression – which allows the original data to be reconstructed – can store an archive of CD audio in half the space, at an average data rate of 750kbps. However, when higher sampling rates and more bits are used to improve resolution, the PCM file becomes unwieldy. It can represent sounds that are quieter than atmospheric noise or at inaudibly high frequencies. With high resolution, the appropriate audio information captured can increase to around 1Mbps, but a lossless file may use 5 to 10Mbps to deliver it, violating a key engineering principle that the channel capacity should match the signal.

MQA solves these problems in two ways, starting with 'encapsulation', which identifies the audio information in the recording; preserves the temporal microstructure; and avoids noise-modulation artefacts. Next, a process called 'music origami' makes the file smaller by 'folding up' extended-resolution information, while packing it underneath the standard audio, below the level of silence. This fits the audio information into a small lossless PCM file of low data rate (typically 1.2Mbps) that is more efficient to stream or download, yet higher in quality than prior methods.

Finally, signalling is added, inaudibly embedding metadata about the recording, playback instructions for the decoder, and a provenance signature. This is completely removed by MQA decoders but remains accessible even if a 24-bit stream is cut down to 16 bits (for example when played over Wi-Fi). Even in these circumstances, the MQA system preserves a large part of the music's temporal microstructure.

This master file, which contains the entire performance, can be checked by the producer for several playback scenarios and authenticated for accuracy on playback. MQA can be played on a Hi-Fi, a smartphone, a portable player, in the car, in a PC, on a Wi-Fi speaker or Bluetooth headphone, and is also backward compatible, giving higher than CD-quality even on a device with no decoder.

Products with a full MQA Decoder unfold the file to deliver the highest possible sound quality. At this level of playback listeners hear what the artists created in the studio.



Region 'B' is compressed and hidden with (C), below the noise-floor of A.

The 'folded' audio behaves like a normal PCM file and can be played anywhere.

An MQA decoder unfolds it to deliver the original recording.

The graph shows the information capacity of 192kHz, 24bit PCM and the audio within it. Region A is the conventional audio information; Region B, higher in frequency, manifests temporal microstructure in the sound; Region C carries noise consequential on the transmission sampling rate

BIOGRAPHY

Bob Stuart, creator of MQA, has been awarded the Royal Academy of Engineering's Prince Philip Medal for his exceptional contribution to audio engineering, which has changed the way we listen to music and experience films. He is a graduate of the University of Birmingham and Imperial College London, where his studies included psychoacoustics and electronic engineering. Bob is an expert in audio coding and was the brains behind MLP (the audio technology at the heart of DVD-Audio, and now part of the Blu-ray Disc specification). And he is, crucially, a dedicated lover of music.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