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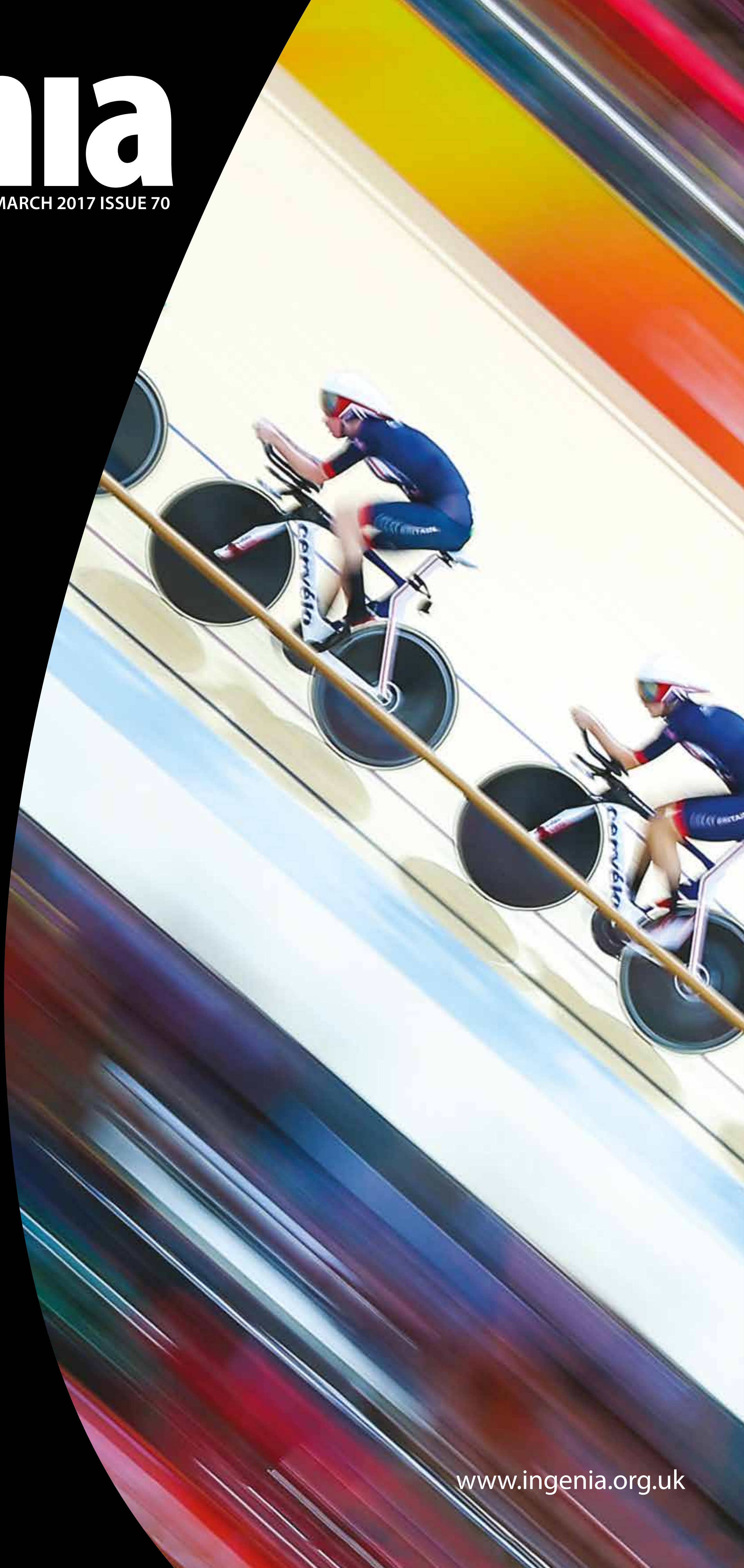

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Editor-in-Chief
Dr Scott Steedman CBE FREng

Managing Editor
Gemma Hummerston

Editorial Assistant
Portia Sale

Director, Policy and External Affairs
Beverley Parkin

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Gemma Hummerston, Royal Academy of Engineering,
Prince Philip House, 3 Carlton House Terrace, London SW1Y 5DG
Tel: 020 7766 0679 Email: gemma.hummerston@raeng.org.uk

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Great Britain's women's team pursuit breaks the world record in qualification at the 2016 Rio Olympics © Simon Wilkinson/swpix.com

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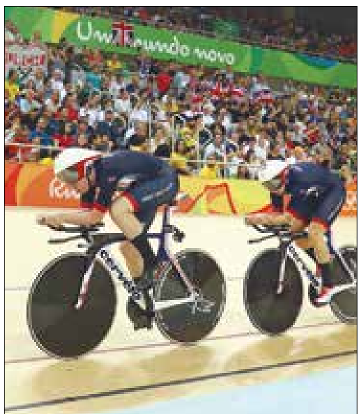

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EDITORIAL

A STRATEGY FOR A DIGITAL FUTURE

Dr Scott Steedman

The government's *Building our Industrial Strategy* Green Paper, published in January, highlights two great challenges for the UK that have hitherto defied solution. The first is low productivity and the second is geography. Not surprisingly, these two issues are linked.

Productivity is a measure of economic output compared to input. Higher productivity is a result of higher efficiency (better use of resources) or higher value in output (per worker, per hour). Comparisons from the OECD (Organisation for Economic Co-operation and Development) suggest that the UK as a whole is some 20% less productive per hour worked than the US, France or Germany, but that the 'productivity gap' is regional. Government data in the Green Paper show that in 2014 productivity in London was 72% above the national average, whereas productivity in Wales, the North East and Northern Ireland was at least 20% below the national average. Tackling the geographic challenge is clearly essential.

The Green Paper outlines a strategy that sets out to "deliver a high-skilled, competitive economy that benefits people throughout the UK". There is a focus on the role of engineering in stimulating growth, and the importance of skills and technical education. The Green Paper promises investment in infrastructure and digital connectivity. What is missing, however, is the bigger picture. The Green Paper lacks an overarching vision of how the strategy will enable the UK to succeed in the rapidly emerging global digital economy.

A digital revolution, or digitisation, must be an important part of any vision of how the UK can tackle the challenges of productivity and regional disparity. At the World Economic Forum in 2013, digitisation was described as the mass adoption of connected digital services by consumers, enterprises and governments. Digitisation has already swept through some industrial sectors (financial services, media) and will inevitably revolutionise others (healthcare, construction). Consumers have seen extraordinary benefits, from online bookings to social media and free communications. Digital platforms including Uber and eBay have challenged historic business models and brought new services to billions of people. The near zero cost of servicing new digital customers enables successful companies to grow at breathtaking pace.

Digitisation brings productivity gains through new business models, new ways of reaching the customer, more efficient production methods and, of course, new ways of connecting employees to their work. There are risks too. McKinsey Global Institute's *Digital America* report, published in 2015, describes the 'hollowing-out' of middle-skilled employment in developed countries, as automation and software replace production and administrative work.

The digital economy, underpinned by engineering and technology, will be transformational because of the revolution it brings in access to markets, both in the ability to reach and connect with customers and the ability of people to offer their labour. Evidence from the McKinsey report shows that 97% of the companies in France that sell online export, compared with just 15% of SMEs without an online presence. Enabling companies to exploit digitisation means that they can readily reach new markets.

A bold and ambitious industrial strategy would tackle the linked issues of low productivity and regional diversity. The goal should be to promote digitisation and to build confidence in the value of investment in automation and production efficiencies in parallel with investment in online platforms aimed at new markets, innovative business models and connectivity with a widely distributed labour market.

None of this will be possible without the physical and digital infrastructure or the education and skills agenda promised in the Green Paper. Successive governments have talked of providing the physical infrastructure needed to create a 'northern powerhouse', and as the Green Paper puts it, to provide "development funding for major infrastructure upgrades". Providing digital infrastructure, intellectual as well as physical, is at least as important if we want to eliminate the UK's internal productivity gap.

Neither of these pillars alone can deliver the real benefits that digitisation could bring to the UK. The industrial strategy has the elements for success. What we need now is for the engineering profession to deploy its unique skills and to seize the opportunities to transform the economy through digitisation; not as a bolt-on enabler of other aspects of the national vision, but as a dominant force that drives innovation and enhances the UK's access to global markets.

Dr Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

INVENTORS OF DIGITAL IMAGING SENSORS WIN GLOBAL ENGINEERING PRIZE

The four engineers responsible for the creation of digital imaging sensors have won the 2017 Queen Elizabeth Prize for Engineering (QEPrize). The winners, Eric Fossum and George Smith, both from the USA, Nobukazu Teranishi from Japan, and Michael Tompsett from the UK, were awarded with the prize for their contributions to revolutionising the way that visual information is captured and analysed. Their work, a collaboration across three countries, reflects the international outlook of the prize. The announcement was made by Lord Browne of Madingley FREng FRS at the Royal Academy of Engineering on 1 February, in the presence of HRH The Princess Royal.

(L–R) Dr Michael Tompsett, Professor Eric Fossum and Professor Nobukazu Teranishi attended the announcement in London on 1 February; and fourth winner George Smith

The QEPrize is an international £1 million prize that celebrates the engineer or engineers responsible for a groundbreaking innovation that has been of global benefit to humanity. Its objective is to raise the public profile of engineering and to inspire young people to become engineers. It is estimated that the announcement reached a potential audience of more than 1.3 billion people through global media coverage in countries including the UK, USA, China and Japan.

The prize was awarded for three innovations spanning three decades that have radically changed the visual world: the charge coupled device (CCD), the pinned photodiode (PPD) and the complementary metal oxide semiconductor (CMOS) image sensor. Together, this image sensor technology has transformed medical treatments, science, personal communication and entertainment. Today's cameras can fit on a fingertip and are found in countless portable devices across the world.

Every second, around 100 cameras are made using CMOS technology, and more than three billion images a day are shared. From uploading photographs and videos to social media, to enabling autonomous vehicles or biometric fingerprint recognition on smartphones and tablets, the global use of digital imaging has grown at a phenomenal rate.

In the 1970s, George Smith and Willard Boyle (now deceased) developed the CCD, which was later used in imaging by Michael Tompsett. The CCD is the image sensor found inside early digital cameras that converts individual particles of light, or photons, into an electrical signal. The charge is then converted into a binary digital form by an analogue-to-digital converter, and the image is stored as digital data.

The CCD was originally intended for use in computer memory, but Tompsett recognised it imaging potential, inventing the imaging semiconductor circuit, complete with analogue-to-digital converter. The following decade, Nobukazu Teranishi invented the modern PPD, which reduced the size of light-capturing 'pixels' and significantly improved the quality of images. The development of the CMOS sensor by Eric Fossum in 1992 allowed cameras to be made smaller, cheaper and with better battery life.

The winners were decided by an international panel of judges, chaired by Professor Sir Christopher Snowden FREng FRS. As well as the £1 million prize, the winners will each receive a trophy at a ceremony at Buckingham Palace later this year. The 2017 trophy was designed by 15-year-old Samuel Bentley, from Wales, winner of the international *Create the Trophy* competition.

More information about the prize and winners can be found at **qeprize.org**

NEW MANUFACTURING HUBS ANNOUNCED

Six new UK research hubs have each received government funding of £10 million to improve the UK's manufacturing processes.

The hubs, formed of partnerships between universities and industry, will explore and improve various manufacturing techniques, each within a specialist area, as a key part of the government's industrial strategy to further UK economic growth. They aim to ensure that the UK creates new products and explores new business opportunities, helping the UK become more competitive and productive.

The new hubs are funded by the government through the Engineering and Physical Sciences Research Council, with additional funding from partners, academia and industry.

Two hubs will focus on medical manufacturing. The Future Manufacturing Hub in Targeted Healthcare, led by University College London, will focus on providing the infrastructure and capabilities needed to ensure that new targeted biological medicines can be developed quickly and affordably. A second medical hub, led by the University of Strathclyde, aims to design a process to quickly and reliably manufacture medicines.

A hub led by the University of Sheffield will explore how powder-based manufacturing processes can provide low-energy, low-cost and low-waste manufacturing. At the Future Composites Manufacturing Hub, led by the University of Nottingham, researchers will look into the development of automated manufacturing technologies that deliver components for sectors such as aerospace, transport, energy and construction.

A hub led by the University of Huddersfield will create embedded metrology systems to be applied across manufacturing, which aim to improve product quality and decrease waste. At Cardiff University, a hub will research large-scale compound semiconductor manufacturing to boost the uptake and application of the technology.

Jo Johnson MP, Minister of State for Universities, Science, Research and Innovation, said: "This investment will lay the foundations to allow industry and our world-leading universities to thrive for years to come and is exactly the type of project that our upcoming industrial strategy will look to support."

FILMS AIM TO INSPIRE LGBT ENGINEERS

A new series of online videos profiling lesbian, gay, bisexual and transgender (LGBT) engineers has been launched by the Royal Academy of Engineering, InterEngineering and Mott MacDonald with an aim to inspire prospective engineers who are LGBT, as well as existing engineers who may wish to come out or transition at work.

Launched as part of LGBT history month, the *What's it like?* video series features 20 successful LGBT engineers, working in a variety of roles and settings, from a nuclear quality director to a lead design engineer in the British Army. The engineers share their stories of being LGBT in an engineering environment, and encourage others to 'be yourself'.

The LGBT engineers who took part in the new video series increasing the visibility of LGBT people in engineering

Dr Hayaatun Sillem, Deputy Chief Executive and Diversity and Inclusion Champion at the Royal Academy of Engineering, said: "Experience of leading our programme to increase diversity and inclusion across engineering tells us that role models have a pivotal role to play in encouraging people to join and stay in the profession. It is really good to see LGBT engineers making themselves visible, and working with us to increase and extend diversity and inclusion across the sector."

UK LGBT History Month is celebrated in February and aims to increase the visibility of LGBT people and their experiences, as well as raising awareness of matters affecting the LGBT community.

The videos can be viewed at **www.interengineeringlgbt.com/lgbt-in-engineering-video-profiles**

ENERGY MARKET TRIALLED IN CORNWALL

A £19 million trial to establish a local energy market in Cornwall will see the development of a virtual marketplace and new technology installed in over 150 homes and businesses. Over the next three years, the trial will test the use of flexible demand, generation and storage, in both business and home settings.

As part of the programme, free smart technology upgrades will be given to renewable energy generators, local businesses and large energy users. These aim to help establish how energy storage, flexible demand and generation can be combined with smart technologies to support the local electricity distribution network. It could also potentially reduce the cost of energy for local homes and businesses. The virtual marketplace will allow users to buy and sell energy to the grid and wholesale energy market.

The trial's findings aim to inform the government, National Grid and regulators on how the UK can develop new and effective markets for flexible energy. It is being funded by Centrica and the British Gas Energy for Tomorrow Fund, as well as a £13 million grant from the European Regional Development Fund.

The trial in Cornwall recognises the key role that flexible, smart energy will play in supporting a secure, affordable and lower carbon system for the UK © Centrica

Jorge Pikunic, Managing Director of Centrica Distributed Energy and Power, said: "Cornwall has been at the forefront of harnessing renewable generation, but that has brought challenges to the local grid. Our ambition is to explore how battery storage, flexible demand and generation can reduce pressure on the UK's electricity grid, avoid expensive network upgrades and support future decarbonisation."

To find out more, please visit **www.centrica.com/cornwall**

REVIEW BACKS PLANS FOR TIDAL LAGOONS

An artist's impression of the Swansea Bay Tidal Lagoon © Tidal Lagoon Power

An independent review of tidal lagoons, commissioned by the government, has supported plans for a £1.3 billion development to be built in Swansea Bay.

The Hendry Review, led by former UK energy minister Charles Hendry, stated that "the evidence is clear that tidal lagoons can play a cost-effective role in the UK's energy mix" and that tidal lagoons could "at scale deliver low-carbon power in a way that is very competitive".

Project scoping, design, feasibility studies and early consultation for Swansea Bay Tidal Lagoon began in 2011, with a development consent order made in 2015. Construction is scheduled to start in 2018. It will be the world's first tidal lagoon power plant – a U-shaped breakwater, built out from the coast, which has a bank of hydro turbines in it. Electricity will be generated on both the incoming and outgoing tides, four times a day, every day.

The review highlighted the benefits to the local economy that a tidal lagoon could bring and that the UK "should seize the opportunity to move this technology forward now".

It is hoped that agreement for the Swansea project to go ahead will lead to further developments across the country. However, Hendry was quick to point out that this should not happen until the first project is operational and a clear long-term government strategy is in place. This includes the establishment of a Tidal Power Authority to oversee the industry.

The full report can be read at **hendryreview.wordpress.com**

REPORT CALLS FOR ENERGY EFFICIENCY STANDARD

A review jointly published by the Department for Business, Energy and Industrial Strategy and the Department for Communities and Local Government has set out a list of key recommendations to improve energy efficiency in the UK and encourage the uptake of renewable technologies.

Each Home Counts (also known as the Bonfield Review) suggests a new approach to how consumers can be properly protected and advised when they install energy efficiency and renewable energy measures in their homes. It proposes the use of a chartermark so that consumers can have confidence in providers, while companies in the sector will have a simplified and certain route to market.

Companies applying to use the chartermark will have to abide by three key elements in a framework: a consumer charter to ensure that all consumers receive excellent levels of customer service, a clear redress process and guarantee protection; a code of conduct that sets out how companies behave, operate and report; and codes of practice so that the risk of poor-quality installation is minimised.

Dr Peter Bonfield OBE FREng, who conducted the review, said: "My review seeks to ensure that in the future conventional measures, such as insulation, always deliver the quality levels and outcomes that consumers have every right to expect, underpinned by the protection, service and advice so critical for householders.

"It also seeks to ensure that new opportunities offered through the rollout of smart meters and other energy efficiency and renewable energy measures fulfil their potential in a way that informs and protects householders."

The independent review was developed with input from across the sector. Feedback gathered since its publication in December will be incorporated into detailed plans to implement the vision set out in the report.

The full report can be read at **bit.ly/2IfsgOm**

MATHS AND ROBOTICS AT THE SCIENCE MUSEUM

The layout of Mathematics: The Winton Gallery has been designed to resemble airflow around a 1929 Handley Page aircraft © Nick Guttridge

The Science Museum has unveiled two new exhibitions that take a look at engineering and the increasingly important role that it plays in everyday life.

The museum opened its permanent *Mathematics: The Winton Gallery* in December. It contains a variety of mathematical objects, such as an early version of the Enigma machine and a 1920s calculator for reinforced concrete. The gallery aims to demonstrate how maths underpins a number of disciplines, including engineering.

Designed by Zaha Hadid Architects, the gallery's main feature is a 1929 Handley Page aircraft, which is enclosed in an overhead structure designed to represent air flowing around the craft. Based on the equations of airflow used in the aviation industry, this design is also incorporated into the gallery's layout.

The Science Museum's *Robots* exhibition, which opened in February, features a collection of more than 100 robots, from a 16th-century mechanical monk to robots from science fiction and modern-day research labs. The exhibition explores more than 500 years of humanoid robots, looking at how robots and society have been shaped by religious belief, the industrial revolution, 20th-century popular culture and dreams about the future.

Originally built in 1928, Eric was Britain's first robot. The model on display at the Science Museum was recreated in 2016, thanks to a Kickstarter campaign © The Board of Trustees of the Science Museum

Visitors will also learn about recent development in robotics research, exploring how roboticists are building robots that resemble people and interact in human-like ways.

Visit the website at **www.sciencemuseum.org.uk**

LETTERS

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

GRAPHENE IS MOVING INTO ITS 'TEENAGE YEARS'

Since the first isolation of graphene at the University of Manchester in 2004, there have been huge expectations for the use of the material in products and applications. From electronics and aerospace to bio-medical and many other markets, there are many areas in which it can be applied. Despite only 13 years since its discovery, and in reality only a few years since industry first became interested following its receipt of the Nobel Prize for Physics in 2010, there has been a huge increase in the number of patents being filed, including many from China and overseas.

As Dr Scott Steedman's editorial in the last issue pointed out ('A Cinderella material', *Ingenia* 69), expectations remain high in terms of commercialising graphene (and other related two-dimensional materials) and its applications. Despite graphene only being in its 'teenage' years, comparisons can be made to other materials such as carbon fibre and silicon, which took many years to reach initial application and many more years to reach wide-scale commercialisation. However, we are seeing some differences to the past and are currently, I believe, in the process of realising the technologies made possible by the properties of graphene.

Here at the University of Manchester, we have established the National Graphene Institute (NGI) and the Graphene Engineering Innovation Centre (GEIC) is currently under construction. We are looking to develop the eco-system through partnership and collaboration between academia and industry to accelerate the development of real products and applications that create value through the supply chain in the UK.

There is no better example of this than the small consortium of academic and business collaborators who produced a graphene-enhanced composite wing on a small aircraft (unmanned aerial vehicle), which achieved a first flight at the Farnborough International Air Show in July 2016. The project has now led to a graphene in aerospace white paper being developed with the Aerospace Technology Institute, which is due to be launched in March 2017. Alongside this, a programme of work to realise a number of potential benefits to the aerospace sector and supply chain in the UK has begun. With the application of good engineering and manufacturing skills and capabilities, we can realise these potential benefits through a collaboration between academia and industry. The involvement and collaboration on standards, measurement and characterisation is also key here and our partnership with the National Physical Laboratory is critical to maintain a UK leading position.

So, whereas some like to count patents as a measure of commercialisation and success, real progress can be measured through partnerships and the launch of new products and applications. While these initial applications are mainly through the addition of graphene to an existing product (known as the 'fast lane' of new product development as it does not generally need the development of new manufacturing process or tools and skills), we are already seeing some good progress across the UK supply chain. I expect to see this increase over the next few years as the NGI develops further relationships and the GEIC opens in 2018. We might just be starting to write our 'future histories'.

James Baker
Graphene Business Director
University of Manchester

MODULAR DESIGN COULD BE KEY ADVANTAGE FOR SMRS

The article detailing the very significant advantages that flow from the introduction of modular design for manufacture and assembly in the nuclear sector could not be more timely ('Manufacturing power stations', *Ingenia* 69). It demonstrates just how much can be gained by paying attention to the non-nuclear aspects of nuclear plants. These potentially amount to a greater part of the overall costs than the very well-established and scrutinised nuclear steam supply system – the reactor, its coolant pumps and associated piping used to generate the steam needed to drive the turbine generator unit – which has been the traditional focus of attention.

In terms of off-site manufacture, massive gains have been made in the construction sector over the last 20 to 30 years. The article clearly shows the advantages of scrutinising all aspects of the construction process from the point of view of design for manufacture and assembly.

Modular construction (making many of the structural components off-site) has already revolutionised many sectors of the construction and infrastructure industry, reducing building times with safer operations during construction and improved quality. The article points out that a fleet of smaller, standardised and manufactured modular reactors could significantly reduce costs and timescales. Equally importantly, the same tools, techniques and methodologies can be applied to the large plants also envisaged in the UK's first wave of new nuclear power plants.

Bringing modular construction techniques that are common in other industries into nuclear projects will remove risk and deliver cost and schedule certainty. Delays in onsite construction present the biggest risk of cost escalation for nuclear plants. Implementing advanced manufacturing, with an increase in off-site modular assembly, will revolutionise the way power stations are manufactured, making nuclear more attractive to investors and lowering the cost of electricity to consumers. As the article pointed out, it is possible that gains of some tens of pounds per megawatt hour could be realised.

Off-site assembly in a clean manufacturing environment gives greater control over the quality of final products. It gives the ability to work with a stable workforce and drives down costs, particularly for nth-of-a-kind components. When integrated with design and manufacturing, modular construction will be a game-changer in assuring delivery to time and cost of major nuclear projects.

Innovative large-scale assembly and manufacturing solutions must be integrated with design to generate a cost-effective manufacturing plant for large nuclear assemblies. A UK commitment to a fleet of small modular reactors (SMRs) as part of a long-term nuclear sector plan provides the opportunity for significant UK engineering innovation, building on the investments made in the design for manufacture and assembly (DfMA) project and in the Nuclear Advanced Manufacturing Research Centre at the University of Sheffield. As part of its *Final Report* recommendations to government, the Nuclear Innovation Research Advisory Board (NIRAB) indicated that supporting UK involvement in 'design for manufacturing and construction' and fuel supply presents an opportunity to develop exploitable design and manufacturing intellectual property, providing direct benefit from export sales as well as UK deployment. The SMR market presents a route to exploitation for a large portion of NIRAB's research and development recommendations, and the development of SMR technologies is a stepping stone to involvement in Generation IV reactor collaboration programmes for the longer term.

Dr Dame Sue Ion DBE FREng FRS
Chair, NIRAB

RESPONDING TO THE BONFIELD REVIEW

The *Each Home Counts* report (also known as the Bonfield Review) was published in December 2016 (see page 7), with endorsements from then Department for Business, Energy and Industrial Strategy Minister, Baroness Neville-Rolfe DBE CMG, and Department for Communities and Local Government Minister for Housing and Planning, Gavin Barwell. The reaction from the residential energy efficiency industry and other stakeholders was almost universally positive or neutral, with many realising that the 27 recommendations would lead to a more professional industry when adopted. The full support of consumer representatives and emerging financial institutions in the sector were both highly significant.

By the time the report was published, its scope had widened to include the smart meter rollout and associated energy efficiency opportunities, social housing and the potential funders of energy efficiency upgrades. It genuinely covered the whole of the industry, allowing all technologies, installations, housing types and ownership models to be treated in the same way. This should take the whole industry forward, not just some parts, delivering a much greater level of service for the end consumer and a larger energy efficiency industry, leading to increased business and jobs.

However, the publication of the review is only the start of the transformation of the industry. The establishment of a new quality mark is perhaps the biggest challenge over the next months, but the coordination of energy advice for consumers, installers and the wider industry, and the formation of a database of all energy-related information on UK dwellings will also take significant efforts from across the industry.

Timescales are important, as future government funding of energy efficiency improvements through the Energy Company Obligation programme, plus upgrades for housing association dwellings, will be only based on the implementation of the review recommendations. Industry groups need to be fully involved in the next steps organised by the workstream leads, and develop the relevant changes to their part of the industry needed to meet the review's recommendations.

The private sector housing market will not be left out of this new future, with very significant finances potentially available from the market. These new investors in the industry will only be in a position to release funds if the full recommendations of the report are adequately implemented. This is a very different model than was adopted in the past, not being reliant on government-based financial schemes.

For the suppliers of energy efficiency equipment, the review and its implementation provides a number of opportunities. High among these is the elimination of non-compliant equipment from the market: "a high-quality installation relies on the use of high-quality and fully compliant equipment." For the majority of the manufacturing industry, this will come as very good news; for those not delivering compliant equipment, an initiative to become compliant, or lose market share.

The role of standards now and in the future will become more important. This is particularly the case as a result of the developing residential refurbishment standard, currently under review by the BSI working group. Upon completion, this standard has the possibility to be the framework for the industry. As many industry stakeholders as possible need to engage with the development of the standard.

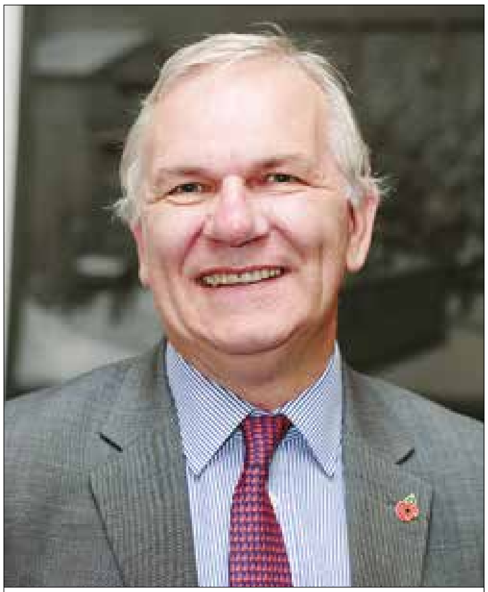
The publication of the *Each Home Counts* report is a significant step in the professionalisation of the residential energy efficiency industry. All stakeholders have the opportunity to contribute to the development of the new industry, for the benefit of consumers, their energy bills, the wider environment and the energy efficiency industry.

Howard Porter
CEO
BEAMA (British Electrotechnical and Allied Manufacturers Association)

OPINION

TURBULENT POLITICS PUT A PREMIUM ON RESEARCH IMPACT

The political landscape in the UK, and the rest of the world, is changing, and with it, so do policies relating to education and research. Professor Graeme Reid, Chair of Science and Research Policy at UCL, argues that this is a time for great opportunities in engineering research.


Professor Graeme Reid

The political context for engineering and science changes almost daily. New legislation on higher education and research; profound changes in the US leadership; devolution debates at both national and city levels; stock markets rising against expectations; an economic backdrop that is ever more difficult to understand; and, of course, Brexit.

I was worried that science and engineering would be squeezed to the margins of politics by more pressing concerns. However, it is clear that science and research are one of the government's priorities. By demonstrating the impact of research, we can keep it that way.

Theresa May placed heavy emphasis on science and innovation in her vision for our future. In her 23 January speech on exiting the EU, and a few days later about industrial strategy, she made clear her intention to attract talented people from around the world, protect research funding, maintain strong international collaborations (not least with EU member states), and to make science and innovation one of the cornerstones of the UK economy. This builds on the surprise announcement in last year's autumn statement of a £4.7 billion increase in science and innovation spending.

The Research Excellence Framework (REF), carried out in 2014, showed how university researchers have been demonstrating more clearly than ever the impact of their work on the economy and society ('Research with impact', *Ingenia* 69). The impact case studies submitted to REF2014 provide an unprecedented archive. The national academies, the Campaign for Science and Engineering, and others can now combine these case studies with economic analysis to demonstrate to government and a wider audience the value of science and innovation.

REF is a valuable catalyst, encouraging academic researchers to more clearly explain the impact of their research. However, it did not set out to capture the full impact of research and higher education. Let us take two examples of impact beyond REF.

About two-thirds of the UK's research investment comes from businesses, and about half of that comes from firms with headquarters overseas, much more

It is easy to think of innovation as something that depends on PhD graduates in businesses and universities. In reality, many firms innovate successfully without doctoral research expertise, using talented people who have qualified through apprenticeships or first degrees to develop improvements in sales, marketing, finance, employment and other key features of a successful business

than other major economies. The UK's outstanding academic research is a magnet to overseas firms who come here to collaborate with, and recruit from, our universities. The government sometimes bemoans the low level of business R&D in this country – imagine what the level would be like without the inward investment from global corporations, attracted to the UK by our strong academic base?

University teaching brings students into contact with the frontiers of knowledge, and the researchers who are stretching those frontiers. An interwoven fabric of teaching and research allows universities to make indispensable contributions to the development of the next generation of professionals. These highly skilled people are a vital part of our knowledge economy. University teaching is under scrutiny like never before, and may well be subject to appraisal under new arrangements going through Parliament. Changes that are introduced must not reduce the impact of university graduates on our businesses, public services and cultural institutions.

Relationships between universities and business – the subject of an influential review by the Royal Academy of Engineering's President Professor Dame Anne Dowling OM DBE FREng FRS – are good, but they need to keep improving. The new industrial strategy promises even more emphasis on commercialising research. The National Centre for Universities and Business is developing software tools to match supply and demand for research collaborations and student placements. We need more innovations like that.

For decades, this country has failed to generate enough people with strong technical skills. The government now promises further investment in that area, but that is only part of the picture. It is easy to think of innovation as something that depends on PhD graduates in businesses and universities. In reality, many firms innovate successfully without doctoral research expertise, using talented people who have qualified through apprenticeships or first degrees to develop improvements in sales, marketing, finance, employment and other key features of a successful business. We need to integrate further education, apprenticeships and first degree skills into the innovation agenda but engage further education colleges more extensively and expand the coverage of innovation initiatives beyond technology into other areas of business management. Wales and Scotland are already making moves in that direction with the closer integration of further and higher education.

Postdoctoral research must also break down barriers between academic disciplines. Many universities, including my own, have made a vigorous start by supporting research in unconventional, cross-disciplinary domains such as bioengineering, sustainable cities and food technology. But we have yet to realise the full potential of collaboration between, for example, engineering and the humanities. The creation of UK Research and Innovation offers much potential to take this further.

Political turbulence brings opportunities as well as threats. As the House of Lords Science and Technology Committee said in a recent report, "an uncertain era is a time for boldness, not timidity". The powerful impact of our research base gives this country something to be bold about.

BIOGRAPHY

Professor Graeme Reid is Chair of Science and Research Policy at UCL. He was specialist advisor to the House of Lords Science and Technology Committee for its work on science and the EU, before and after the 2016 referendum on UK membership of the EU. Professor Reid is also Chairman of the Campaign for Science and Engineering, a Trustee of the Association of Medical Research Charities and Strategic Advisor to the National Centre for Universities and Business.

The Rosetta spacecraft was launched in March 2004, on a 10-year journey towards comet 67P/Churyumov-Gerasimenko. In January 2014, it 'woke up' from deep space hibernation and prepared for arrival at the comet in August that year. In November, the mission deployed its Philae probe (shown here as an artist's impression as it is deployed) to the comet © ESA/ATG medialab; Comet image: ESA/Rosetta/Navcam

COMMUNICATING WITH OUTER SPACE

The technology that enabled the precise control of the pioneering Rosetta spacecraft and enabled the Philae probe to make the first ever soft landing of a spacecraft on a comet was awarded the Royal Academy of Engineering's Major Project Award in June 2016. Technology journalist Richard Gray speaks to Nick James, Radio Systems Team Leader at BAE Systems and part of the engineering team that developed the technology.

Drifting downwards, the Rosetta space probe snapped a few final close-ups of the comet it had spent nearly two years circling. As the spacecraft, the size of a family car, settled on the surface of the distant Comet 67P/Churyumov–Gerasimenko, it marked the end of an extraordinary piece of exploration.

Rosetta had travelled almost eight billion kilometres through the solar system as it chased and orbited the comet. The data it sent back provided unparalleled insights into objects that are normally only experienced as transient pinpricks of light in the night sky. As the images taken in the final moments of the probe's mission appeared on the screens at the European Space Agency's (ESA) Operations Centre in Germany, they highlighted the feat of communication that made the entire endeavour possible.

Transmitting data across 719 million kilometres of space from just metres above the comet's surface is an achievement in itself. Yet the radio communications between Rosetta and the scientists back on Earth did far more than simply exchange data; they enabled the scientists to reach the comet in the first place.

HITTING THE MARK

Underpinning the infrastructure of the ground stations used during the mission was the Intermediate Frequency Modem System (IFMS), a powerful satellite modem system developed by BAE Systems. In addition to untangling the 350 gigabytes of data beamed back by Rosetta, the system enabled precise calculations of the spacecraft's position, acting like a GPS for the solar system.

It was a crucial tool in allowing the spacecraft to navigate during its 6.4 billion kilometre journey from Earth to the comet, a target only four kilometres wide and moving at 135,000 kilometres per hour. Some of those working on the mission have compared this to trying to toss a grain of sand through the eye of a needle from 16,000 kilometres away. A tiny error would have seen the spacecraft fly wide of its mark, ending the mission in failure.

The secret behind this achievement can be traced to more than two decades ago, when ESA decided to upgrade the ground stations it was using to pick up radio signals from its spacecraft. At the time, a technology called software-defined radio was starting to emerge. Rather than using the analogue components found in traditional radios to tune to the signal, filter and demodulate it, this technology converts the raw signal into digital bits from which processors and software can extract the necessary information. It has the key advantage of flexibility, enabling the radio to change function with just a change of software.

BAE Systems had already been using software-defined radio in some commercial and military applications in the early 1990s, and this experience led to its successful bid to develop the technology ESA needed to communicate with its future space missions.

However, one of the biggest challenges was meeting

Data sent from the Rosetta spacecraft to ground stations, such as this one in Malargüe, Argentina, was translated by the Intermediate Frequency Modem System. This allowed scientists to reach the comet with the craft and target the landing of the Philae probe © ESA–D. Pazos the ESA's extremely tight requirements for preserving the quality of the signals received from distant parts of the solar system. Degrading those weak signals when processing them, even by a small amount, could render them useless.

A key aspect of maintaining signal purity is the process of converting the analogue radio signal into a stream of digital samples. BAE Systems used a number of novel techniques to improve the performance of a commercial signal converter to the point where it would meet ESA's exacting requirements. Once converted to digital form, most of the subsequent processing is done using a type of microchip known as field programmable gate arrays (FPGA). These consist of logic blocks that can be wired up to handle complex computations in parallel rather than in sequence, which is what occurs in most traditional software. This allowed the designers to develop sophisticated algorithms that could maintain a high level of purity and stability as the radio signals were processed.

The ability to perform computations concurrently ensured that the quality of the data itself was preserved, while allowing the system to extract additional information to calculate the spacecraft's position from the radio signal. At the time the IFMS was being built, there were two main ways of doing this.

The first approach uses the Doppler effect: the change in wave frequency as two objects move in relation to each other. By looking for this in the signal beamed back by the spacecraft, it was possible for scientists to work out how fast it was moving relative to the Earth.

The second uses a method known as ranging, which involves beaming a unique sequence of tones within a signal to the spacecraft, and measuring the time it takes for it to be returned to Earth. Using the speed it takes light to travel through the near vacuum of space, and the known time it takes for the spacecraft to turn the pulse around, it is possible to work out the vehicle's distance from home. However, ESA wanted its new technology to have a lifetime of at least 15 years, which meant that the team building IFMS had to ensure it could cope with the future.

DECODING DATA

Traditional computer chips process information in a pipeline, so that each chip does one job before passing it along to the next. However, the IFMS engineers decided to build multiple interconnections between the 24 microchips involved in processing the signals so that data could be shunted back and forth.

In the early days of the IFMS's operational life, there was no obvious need for this level of complexity in the nine ground stations where it was installed. The processors were more than capable of easily handling the amount of information received through their antennas, yet the technology was to prove crucial later for the IFMS system and the Rosetta mission. Around 2005, ESA began a series of audacious planetary missions that were unlike any it had tried before. To realise these, it needed to use a third and relatively new technique for tracking spacecraft.

Delta Differential One-way Ranging (delta-DOR) had not been considered necessary when the IFMS was being put together in the 1990s. With the system's inbuilt flexibility, engineers were able to write new software for it that would make the system possible. They added the completely new function without the need for new hardware.

Delta-DOR is, in essence, relatively simple. By listening with two ground stations simultaneously, it is possible to measure the time difference between each station receiving a signal from a spacecraft and to use this to triangulate the spacecraft's position. In practice, it required some dramatic changes to the way the IFMS had been originally designed to handle signals. Rather than locking to a single signal and demodulating that, it instead began being used to record large chunks of the radio frequency spectrum, which could be processed later. This approach, known as open-loop recording, is like listening to a room full of people all talking at once. Rather than focusing on what just one person was saying, open-loop recording stores what everyone said so you can search through it later to find the conversation you were looking for. This system makes it possible to search for specific features within the signals broadcast by a spacecraft, and tag them with a time stamp when they are received by each ground station. However, the arrival time at each station can also be affected by a number of sources of error, such as the time it takes for radio waves to travel through the different thicknesses of atmosphere above each ground station, or errors in the clocks at the stations.

To overcome such errors, open-loop recording can also be used to simultaneously track the radio waves coming from a quasar (a galaxy-sized black hole that emits vast amounts of energy) in the same part of the sky as the spacecraft sending the signal. Quasars emit a noise-like signal in a random waveform that is received by both ground stations. The two waveforms are slid past each

USING DELTA-DOR TO PINPOINT A SPACECRAFT

By recording the signals received by two ground stations – one just outside Madrid and the other outside Perth in Australia, for example – it is possible to find the time when a specific wave pattern arrives at each.

As the distance between the two stations is known, this timing information can be used to work out the angle that the radio signal came from. For example, if the arrival time is exactly the same, then it means the ground stations sit at either end of a right-angled triangle.

If one ground station receives the signal from the spacecraft slightly sooner than the other, then it means that the spacecraft is off to one side. Using this to draw invisible lines back out into space, the spacecraft can then be pinpointed at the point where they intersect.

other in a correlator to look for a match, and this correlation peak reports the timing offset between the two recordings. Scientists can then use this to work out the direction the radio signal came from at each ground station and trace them back as invisible lines to a point where they intersect. This technique allows ESA's scientists to work out the position of a spacecraft to an accuracy of one kilometre for every 100 million kilometres it is from Earth. It has proved crucial for modern missions probing distant parts of the solar system and its planets. While space is mostly empty, it is also not quite a vacuum. On journeys that cover millions, if not billions, of kilometres, spacecraft can drift from their original path. Even tiny disturbances such as the pressure of sunlight on a spacecraft can be enough to push them off course.

Spacecraft also rarely travel directly to their destination. There are no rockets on Earth powerful enough to provide the boost needed to travel those sorts of distances. Instead, spacecraft take circuitous routes that slingshot around planets to build up the speed they need with the assistance of gravity. Rosetta used four such gravity assists to reach comet 67P – three around the Earth and one around Mars. If the trajectory is even slightly wrong, the spacecraft will either fly fatally into the planet or whizz past without picking up enough energy.

Once a spacecraft leaves our atmosphere, it can still be directly observed by large optical telescopes, even when it is a few million kilometres away. However, in most cases, optical tracking cannot currently achieve the accuracy of radio-based tracking and it cannot be used for spacecraft that are further than a few million kilometres away. From the first moments after its launch in 2004, Rosetta was reliant upon the navigational techniques enabled by the IFMS to reach its target 10 years later.

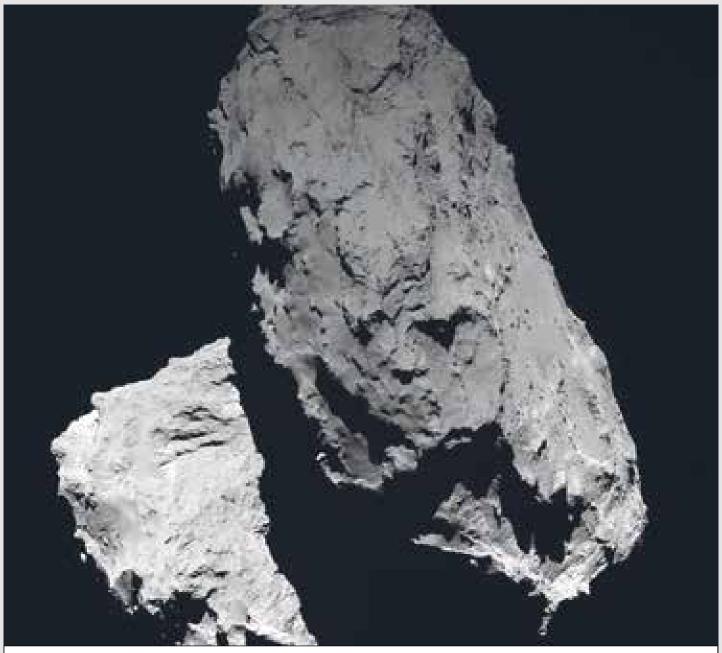
At Rosetta's furthest point from Earth, signals took over 40 minutes to get back, and for other space missions, the communication time lag can be even greater. An experiment to test whether IFMS could be used to support American spacecraft saw it receive a signal from Nasa's Voyager 2 spacecraft that took 10 hours to travel just one way. With these long time lags, it becomes crucial to know exactly where the spacecraft is to ensure it stays on course.

The IFMS played a vital role in a key moment of the Rosetta mission. In 2011, the spacecraft's orbit took it so far away from the Sun that it could not generate enough electricity on its solar arrays to keep all of its instruments going, so it was put into deep-space hibernation.

For this 31-month segment of its journey, the spacecraft essentially shut down as it raced through the solar system without any contact with Earth. Before it went into hibernation, the spacecraft was given commands to put it into a spin to help keep it on a stable course. To check that it was spinning correctly, ESA's mission team used the IFMS open-loop recording feature to look for variations in the carrier signal as it rotated.

Later, as the probe neared the comet, Doppler measurements and the delta-DOR technique helped to tweak its trajectory so that it slotted into orbit around the comet. They also proved vital in ensuring that the spacecraft was on the correct trajectory to release the Philae lander to touchdown on the comet's surface.

ROSETTA: THE COMET CHASER



This image of comet 67P/Churyumov–Gerasimenko was photographed by the Rosetta spacecraft when it was 22.8 kilometres away © ESA/Comet on 29 September 2016 – OSIRIS wide-angle camera

Launched in 2004, the Rosetta mission clocked up a litany of firsts in its 12-year mission to rendezvous and orbit the comet 67P/Churyumov–Gerasimenko.

It marked the first time that a spacecraft had landed on the surface of a comet. Earlier missions had flown past comets, and in one carried out by Nasa, the spacecraft smashed into one.

The Rosetta probe had a small lander called Philae onboard, which descended down to the comet's surface in November 2014. Sadly, a fault with its harpoon system saw it bounce twice on the surface and settle on a dark ditch beneath a cliff face. Unable to get enough sunlight on its solar panels, it quickly ran out of power, but not before sending a few images from the surface along with a treasure trove of data back to its mothership orbiting above.

Despite the setback with Philae, the data collected by Rosetta and its little lander revealed the turbulent lifecycle of comet 67P and how its surface is continually reshaped by geysers of water vapour that shoot out as it turns into the Sun's glare. It also discovered free oxygen in the thin atmosphere surrounding the comet.

TECHNOLOGY THAT EVOLVES

Today, nearly 15 years after IFMS was first put into operation, the system is operating at the very limits of what it can manage. It was designed to handle 20 MHz of bandwidth at a time and now all of its processors are working at full capacity.

To keep it working with technology that dates from the 1990s – and gives it only slightly more signal processing power than found in modern smartphones – BAE Systems' engineers have become efficient at writing software by stripping out unnecessary bits of an algorithm that might use up precious processing power whenever they update the system.

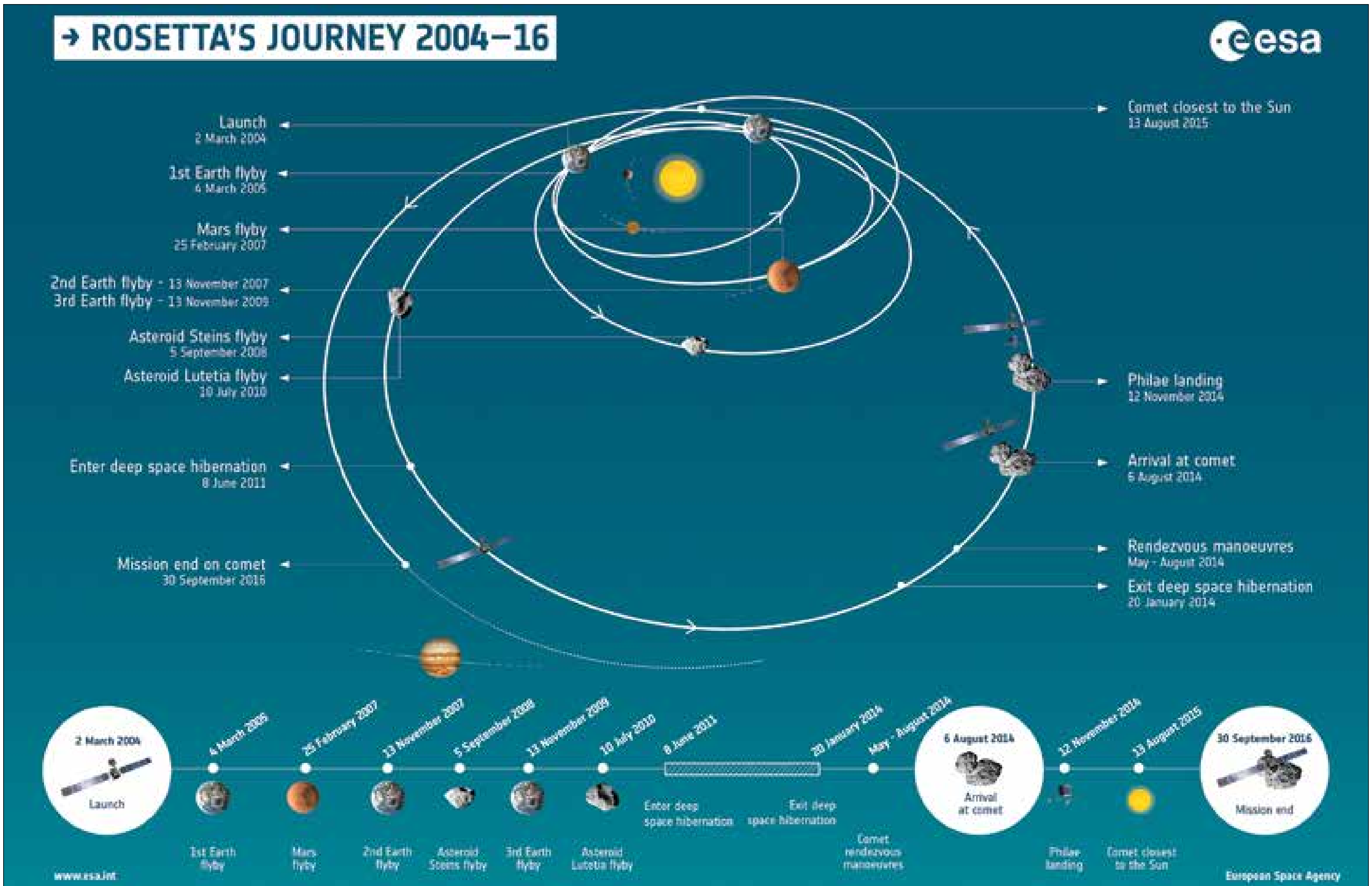
Fortunately, BAE Systems and ESA are now developing a successor to IFMS. The Telemetry Telecommand and Control Processor (TTCP) will be capable of handling 600 MHz of bandwidth simultaneously, 30 times more than IFMS. Just one of TTCP's 24 processing chips will have the capacity of all 24 chips in the IFMS, and this extra power will be crucial for the future missions it will support. One of these will be ESA's Euclid mission to map the dark energy in the universe, which is due to launch in 2020. Its huge cameras will generate so much data that it will need to send back 70 Mb every second.

The improved navigational capabilities will also benefit missions such as ESA's BepiColombo mission to Mercury. Due to launch in 2017, one of its scientific goals is to search for violations to Einstein's Theory of General Relativity. To do this, ESA's scientists will need to determine the spacecraft's position to an accuracy of just 10 centimetres as it orbits a planet that is 77 million kilometres away.

Yet even as engineers begin to think about rolling out this new system in the next year, IFMS has provided a final demonstration of what it has made possible. At the end of September 2016, Rosetta was given commands that sent it on a collision course with the comet it had been orbiting. However, Rosetta was not to go out in a blaze of glory like many other space missions; instead, it glided at a crawling pace to touch down delicately on the dusty surface. It was an impressive finale to the spacecraft's precisely controlled ballet through the solar system.

BIOGRAPHY

Nick James is an Executive Engineer at BAE Systems Applied Intelligence and a BAE Systems Global Engineering Fellow. He is an engineer with more than 20 years of experience in the application of complex signal processing hardware and algorithms to radio systems, particularly in the space communications and spacecraft tracking field.



Rosetta's long journey through the Solar System involved three fly-bys of the Earth and one of Mars, each of which needed to be targeted very precisely to give it enough energy to get to the comet. Throughout this time, the Intermediate Frequency Modem System was used to communicate with the spacecraft and measure its position © ESA

The Stavros Niarchos Foundation Cultural Center behind the seawater canal, with the grass-roofed library (right of image) and the opera house capped by its remarkable slender ferrocement canopy (centre). An additional technical challenge was the mast towering 40 metres above the canopy, which had to be strong enough to resist hurricane speed winds, yet flexible enough to sway visibly in a light breeze. The fibreglass mast was manufactured in what is believed to be the world's longest autoclave (pressurised oven) in Genoa © Michel Denancé

DESIGN-LED INNOVATION AND SUSTAINABILITY

The Stavros Niarchos Foundation Cultural Center, the new home of the Greek National Opera and the Greek National Library, boasts an eye-catching feature, perched on steel columns over the opera house – an innovative, slender canopy that is the largest and most highly engineered ferrocement structure in the world. Engineer and writer Hugh Ferguson talked to Bruce Martin from Expedition Engineering, Darren Barlow from Arup, and David McAllister formerly of Arup, to uncover the engineering behind the project.

The prototype section of the canopy with its twin ferrocement shells and steel bracing being load tested in Athens. When the structure safely survived its anticipated failure loading, the team added concrete blocks to see when and how it would collapse, but they did not induce failure
© Expedition Engineering

Located in Athens, Greece, the Stavros Niarchos Foundation Cultural Center (SNFCC) is a modern monument to the values of culture, learning and humanity. The new cultural centre is funded entirely by the philanthropic foundation established in 1996 to perpetuate the legacy of the wealthy Greek shipping magnate Stavros Niarchos. The Stavros Niarchos Foundation (SNF) supports projects that are expected to achieve 'a broad, lasting and positive impact for society at large'.

It was this vision that led to two important drivers for the project's design. The SNF wanted something that would inspire and benefit all Greeks, not just the minority of opera buffs and bibliophiles. This meant extending the uses of the building, and making it and the surrounding park as accessible and attractive to the public as possible. Secondly, from the start, there was a determination to achieve the highest levels of sustainability. A target was set (which has now been achieved) to make this one of the first buildings in Greece to achieve the US Green Building Council's LEED (leadership in energy and environmental design) Platinum standard. This was made difficult by Athens' hot and humid summers, and by the overriding need to conserve scarce water supplies.

A DRAMATIC VIEW

The site chosen was a large plot (to include a 21-hectare public park) in the southern district of Kallithea, which translates as 'beautiful view'. Kallithea was once a major port for Athens, but rapid urban development in the 20th century detached the site from the water. The project's architect Renzo Piano resolved to restore this connection visually if not physically. He conceived the idea of an artificial hill on which a sloping park would be created, rising 30 metres to a large public space on the roof of the opera house, with views out across the water, and a view in the opposite direction to the ancient Parthenon, an earlier monument to Greek learning and humanity. He also envisaged a huge 400-metre-long by 30-metre-wide seawater 'canal' along the south-west side of the park, prevented from physically connecting to the sea only by a modern ring road. This would also help to create a cooler microclimate for the site.

A key to meeting the sustainability objectives was to make the building as close as possible to carbon neutral. This meant a combination of designing the building and its systems to use as little energy as possible, and harnessing renewables to provide a substantial part of that energy. For the latter, the engineers made a bold claim at the design team's first workshop at the start of the project: with Athens' intense sunlight, a sufficiently large array of photovoltaic (PV) cells could provide all the renewable energy that the building required, thus eliminating the need for unsightly wind turbines or less efficient ground source heat pumps. If the cells could be mounted on a canopy over the opera house, this could also provide shade for the rooftop public space and help reduce solar gain in the building below, as well as providing a striking distinguishing feature for the centre, visible from a distance. The canopy became a key feature of the project.

The engineers' initial concept was for a tensegrity structure – one where rigid struts taking compression are connected by thin cables that are always in tension, which produces a light structure with struts that appear to float in space. With help from the University of Cambridge, where a prototype was created and a PhD thesis prepared, all was proceeding satisfactorily and by summer 2010 the final construction design phase was just starting, but the architect Renzo Piano was not happy. In the 1970s, he had made his name (with Richard Rogers and Arup) designing the Centre Pompidou in Paris, with a design that turned the building inside out and introduced the public to exposed services and structure. With the SNFCC he wanted the opposite: a simple canopy, with no overt details of struts, cables or associated services.

Piano called a meeting of key members of the design team to his head office in Genoa, Italy, to brainstorm a solution. He wanted a structure that would be durable in a marine environment, support the weight of the PV panels under seismic loading, and protect

HISTORY OF FERROCEMENT

Ferrocement was invented by French gardener Joseph-Louis Lambot in the 1840s. He found that by embedding fine meshes of iron wire in a thin layer of hydraulic cement/sand mortar, he could produce a material that was light, strong, cheap, water resistant and easy to form in irregular shapes. He recommended his 'ferciment' as a replacement for wood anywhere that water resistance was important, such as floors, water tanks and planters, and he used it to build a rowing boat. His invention pre-dated reinforced concrete.

Joseph-Louis Lambot's ferrocement rowing boat
© Jorune, Wikimedia Commons

Demonstrating the thinness of the SNFCC's shell © Expedition Engineering

However, producing the wire mesh at that time was labour intensive, and the production of larger diameter bars, and later the introduction of steel bars, led to ferrocement being overtaken by reinforced concrete and largely forgotten for a century.

The idea was picked up by Italian structural engineer Pier Luigi Nervi who was commissioned during the Second World War to design ferrocement boats. In 1945, he built one of his own – a 165-foot-long yacht with a hull 35 millimetres thick. He included ferrocement elements in his subsequent buildings, such as his celebrated 94-metre-span Hall B for the Turin Exhibition in 1948-49, and later used the material as permanent formwork for buildings including those for the 1960 Rome Olympics.

Since then, ferrocement has had a niche following among engineers who appreciate its fine qualities: potentially cheap and simple to make with no formwork required (although formwork was used in Athens), surprisingly elastic, resistant to cracking because of the close spacing of the steel wires (and hence durable when wet), and easily formed into complex shapes. Applications have included: specialist roofs, notably in the Middle East; water tanks in India; low-cost housing in the developing world; large-scale sculptures; 'concrete canoes' built and raced by engineering students throughout the world since the 1970s; and low-cost yachts, particularly those built by enthusiasts such as the SNFCC's architect Renzo Piano. The canopy for the SNFCC in Athens is the world's first ferrocement structure of this scale.

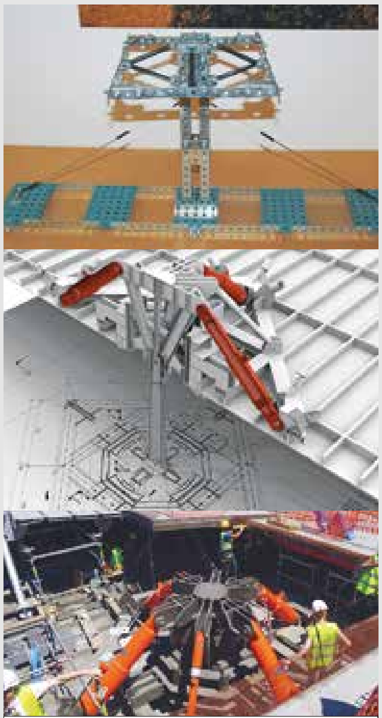
against sun and rain, with a perfectly smooth underside with no visible joints and an exceptionally thin edge. It had to 'float' over the opera house with a minimum of heavy columns. It had to be capable of being built, and demonstrably so in order to give contractors sufficient confidence to submit competitive tenders. The design also had to be complete and ready to go to tender within eight months, as the client was not prepared to delay.

FINDING FERROCEMENT

Options for the surface finish including plywood, steel, aluminium, ceramic and conventional reinforced concrete were debated and discarded, and eventually ferrocement (ultra-thin reinforced concrete) was chosen. It was a bold choice: apart from Renzo Piano, who had built his yacht in ferrocement, none of the design team had direct experience of the material. Although it was invented in the 1840s and used intermittently since the 1940s, it had never been used in the way envisaged for the cultural centre. Expertise and research were limited, there were no appropriate codes for guidance, and time was quickly running out.

Initial evaluation showed just how suitable the material was in

SPRINGS IN THE SKY


The column-head springs to support the canopy: an early Meccano model to test the concept (top); a 3D model to aid construction (middle); and a completed column head in place (bottom) before installing the ferrocement panels over the top. The large orange elements are the fluid polymer springs © Expedition Engineering

The 100 metre by 100 metre solar canopy is inherently a very stiff structure that has to cope with a number of loading challenges: wind loads that can create very high local stresses, with large forces on the columns; large seismic loads, both vertical and horizontal; differential and variable settlement of the opera house underneath; and, in particular, the 'banana' effect as the top skin warms and expands in the sun, tending to pull the centre of the structure upwards.

To tackle these factors, the engineers came up with a novel scheme for a 'machine' in which a system of springs and dampers connects the head of each of the 30 columns to the canopy in a 'soft' manner. This effectively reduces internal stress concentrations in the canopy and reduces the peak reactions on the roof of the opera house by as much as 40%, therefore reducing the structure needed within the opera house to transfer the load to the foundations. It also optimises the dynamic performance of the canopy under wind or seismic loading, and increases the predictability of the internal forces for which the ferrocement is designed.

Conventional structural analysis software is not well set up for understanding and developing such mechanical systems, so physical modelling was central to the design process. This began with modelling in Meccano, followed by bespoke numerical kinematics modelling, 3D printing with mechanical springs, developing a full design in BIM (building information modelling), and finally building and testing the column head system at full scale.

Each column head includes a stiff steel frame fixed to the ferrocement, four springs providing for movement up to +/-150 millimetres, dampers to dissipate energy from wind and seismic movement, and low-friction bearings for robustly and rigidly carrying large lateral loads. At the suggestion of the contractor's engineers, fluid polymer springs were chosen, adapted from the buffers of French TGV (high speed) trains. This had the added advantage that, on the completion of construction, the act of pumping the fluid polymer into the springs allowed the canopy to lift itself from the temporary scaffolding quickly and safely.

Sensors within the column heads continue to be monitored by telemetry, validating predictions, including an actual 100-millimetre bowing movement under differential thermal loads.

this context. It is straightforward to construct, with multiple layers of wire mesh, a conventional cement/fine sand mortar that covers the mesh by just three millimetres, and the top surface is finished with a plasterer's trowel. It is highly durable and requires no over-cladding panels, which could degrade, warp or deteriorate over a long design life. It is well suited to prefabrication and seamless splicing: the small diameter (as little as 0.8 millimetres) and close spacing of the wire mesh and bars means that only small overlaps are needed to maintain structural continuity over the splices. Plastering techniques help to create smoothness across joints. It can be formed into curved shapes and – most importantly – it is (at only 20–25 millimetres) an order of magnitude thinner than an equivalent reinforced or post-tensioned concrete structure. It also has a better strength-to-weight ratio, so reduces the load on the opera house beneath.

Some UK expertise was brought on board, notably independent consultant Patrick Jennings and the University of Manchester's Paul Nedwell, and the project's engineers learned the artisan skills of making ferrocement samples in the university laboratories. More than 100 large panels were then produced for extensive testing at the National Technical University of Athens.

Meanwhile, the structural form was developed: an upper and lower shell separated by hidden steel bracing spanning in both directions, with shells coming together at the


The tight packing of PV cells on top of the canopy was achieved by laminating the panels so that they can be walked on, which removes the need for maintenance walkways © Michel Denancé

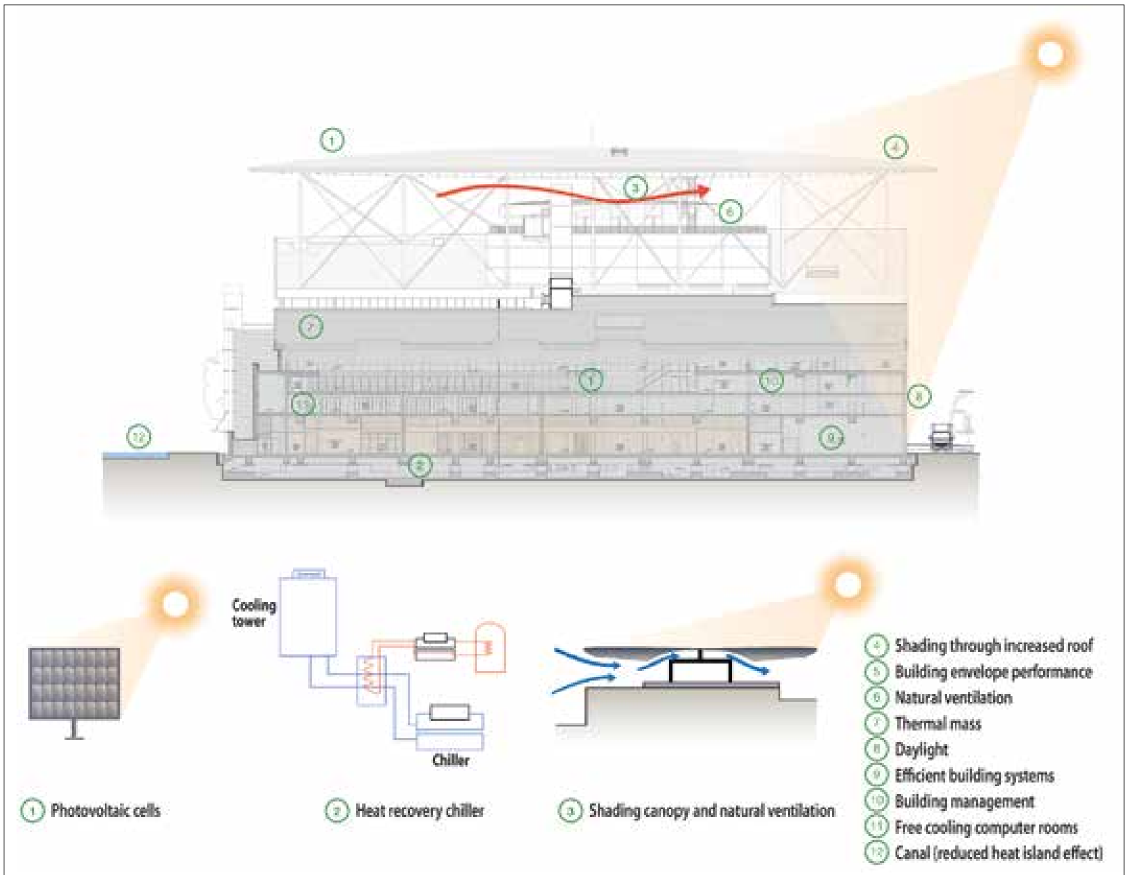
A particular challenge was how to run a large and inflexible high-voltage cable down from the PV cells on the canopy, invisibly and allowing for the large movements of the roof. The solution was an elegant spiral sculpture, which happens to support and contain the cable and effectively absorbs any movement © Michel Denancé

perimeter to produce the sharp edge required by the architect. Adding to the challenges of design and analysis were the non-linear characteristics of ferrocement, including micro-cracking and long-term creep, as well as the arduous loading criteria, particularly from large horizontal and vertical seismic movement. No suitable software was available, so the engineers developed their own in-house software from first principles. To convince everyone, particularly sceptical contractors, that it was buildable, a full-scale 15 metre by 6 metre prototype of a section of the main canopy was constructed and load tested by local labour.

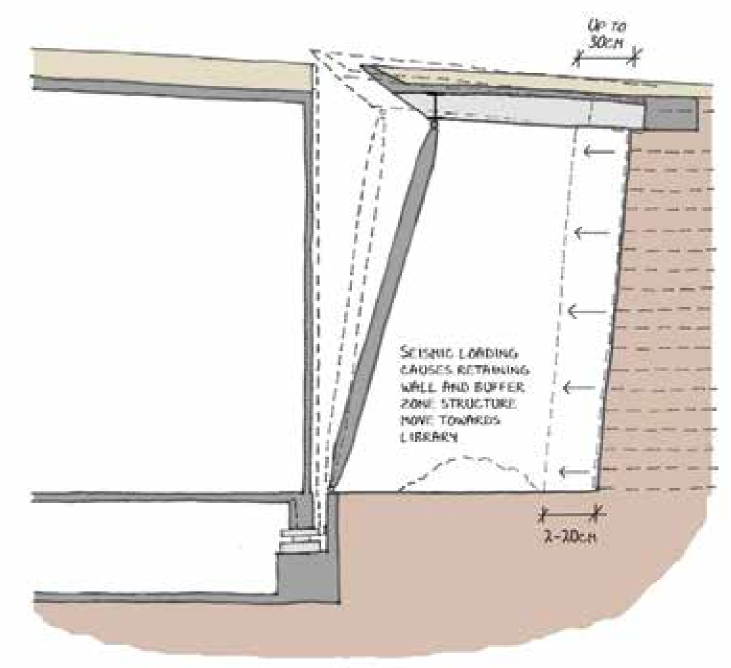
EFFICIENT DESIGN

The 'floating' effect 14 metres above the opera house is created by supporting the canopy on 30 slender cylindrical steel columns, braced by diagonal cable ties. Designing a connection detail between the column heads and the canopy proved the greatest engineering challenge of all. All of the inverters and transformers for capturing energy from the PV cells and converting it to high voltage are contained and hidden within the canopy.

Two factors threatened to limit the power output from the PV cells on top of the canopy: the limited efficiency of available units, and the need to leave space between the cells for maintenance walkways. The first was addressed by specifying outputs beyond what could be achieved, in the (correct) expectation that designs would improve by the time of procurement. The second led to a laminated glass coating, allowing each cell to carry the weight of two booted workers carrying a spare cell. The glass slightly reduced the efficiency, but this was heavily outweighed by allowing the cells to be closely packed with just a small separation for air flow.



The 12 key elements of the sustainability strategy for the SNFCC building © Michel Denancé



The 'buffer zone' between the artificial hill (right) supporting the sloping park and the library (left), allowing the hill to move more than 70 centimetres relative to the library under seismic loading without touching the building. At park level, the gap between is covered with a grating that acts as the hidden intake for the building's ventilation system © Expedition Engineering

The final result is a 100 metre by 100 metre PV array made up of 5,560 panels delivering 1.3 MW (megawatt) of power, and expected to generate 2 GWh (gigawatt hours) per year, similar to powering 650 UK family homes. Additional power will be required from the grid at peak times, but at other times the PVs will feed surplus power into the grid.

The key to seismic protection for the building is the network of 320 pendulum base isolators underneath it, which reduce lateral seismic loads by 80%. Underlying soils are a mix of liquefiable sands and clays that can be softened. The building was effectively isolated from these by piles down to bedrock, but the artificial hill had to be protected with reinforced earth-retaining walls and localised stone columns sunk into the existing ground. A 'buffer zone' isolates the building from the hill.

The buildings themselves are much more conventional in design than the canopy, mainly using reinforced concrete, Greece's most common building material. As part of the sustainability strategy, the buildings are, where possible, 'layered' like onion skins, with the most sensitive, carefully controlled environments (such as the rooms containing precious manuscripts) at the centre and rooms with greater tolerance to variations in temperature and humidity on the outside. Shade reduces solar gain, in particular the canopy over the opera house and carefully designed, retractable roller blinds on the glazed façades. The sloping park, which rises over the top of the library in the form of a grass roof, improves thermal insulation. Good insulation, low-energy lighting and extensive use of a highly efficient displacement ventilation system help to keep energy demand down. Air

The air-handling unit supplying conditioned air into the opera theatre. The large ducts require lower air velocity and smaller fans, resulting in less noise close to the auditorium © Michel Denancé conditioning is still required, but its efficiency is increased by the use of heat recovery chillers. These recycle the heat rejected by the air conditioning to pre-heat domestic hot water from 20°C to 47°C, leaving conventional gas-fired heaters to do the rest.

All of the plant had to be hidden, with only limited space. Grey-water (all waste except from toilets) collection tanks are in the undercroft, and the large air intakes are through gratings in the park floor in the 'buffer zone' where the park joins the library roof. The chillers are discreetly located by the car park. In the vicinity of the opera house auditorium, the plant also had to be silent, leading to large low-ventilation ducts requiring relatively little fan power.

The net effect of all these measures is an estimated reduction in annual energy consumption of more than 40%, compared with a 'standard' building with an identical geometry and in the same location. The 1,400-seat auditorium had a successful 'test run' in November 2016 when it hosted a speech by then President of the United States, Barack Obama, and the centre is due to be commissioned in stages over the early months of 2017, after which it will be handed over to the Greek State.

WATER SELF-SUFFICIENCY

Athens' climate combines hot, dry summers with flood-risk storms, which created challenges for irrigating the 15-hectare sloping park without drawing on scarce potable water supplies. It led to the development of innovative water and drainage solutions including SUDS (sustainable urban drainage system) and rainwater harvesting.

The first measure to conserve water was the choice of plants for the park: native Greek species and other Mediterranean plants that are relatively tolerant of dry conditions and require minimal irrigation. The principal water source is brackish groundwater from four boreholes on the edge of the park, which has to pass through a desalination plant before use. This is supplemented by seawater drawn from the bay and pumped across a bridge over the ring road to the site for desalination. The seawater is also used to refresh the 'canal' that runs along one side of the site.

Onsite surface water attenuation is provided throughout the park in the form of geocellular tanks and deep gravel trenches. Both act to store water during times of heavy rainfall, which protects the municipal drainage system from being overloaded and allows for infiltration to recharge the aquifer © Michel Denancé

All of the rainwater falling on the canopy over the opera house is caught in an invisible gutter along the perimeter, channelled within the canopy, dropped down pipes inside the steel columns supporting the canopy, and carried to buried gravel trenches located throughout the park that infiltrate the rainwater and allow it to recharge the aquifer below the park.

Stormwater in the park, particularly from the hard surfaces of the paths, is collected in drainage channels and carried to the gravel trenches and a set of buried, geotextile attenuation tanks. These serve two purposes: they absorb much of the water from a peak storm, so prevent overload on the local stormwater drainage system; and they allow the stormwater run-off to permeate the ground and also recharge the aquifer. This is designed to cope with anything up to a 1-in-50-year storm. For anything greater and up to a 1-in-200-year storm, part of the park would be allowed to flood. Water from the seawater canal would rise to inundate the surrounding paths, but not the cultural centre itself.

Within the buildings, water demand is reduced by measures such as low-flow appliances and fixtures and waterless urinals. Grey water (all waste except from toilets) from the opera house is collected, filtered, and where necessary treated, stored and then recycled for uses such as toilet flushing.

Altogether these measures reduce the development's impact on the local water utility infrastructure by 37,000 cubic metres, equivalent to 15 Olympic swimming pools per year.

BIOGRAPHY

Bruce Martin is an Associate Director at Expedition Engineering. He led the structural engineering design of the SNFCC. Bruce has a keen interest in elegant, innovative and practical engineering solutions that provide a clear benefit to the client.

Darren Barlow was the Project Director for the SNFCC project. He has over 25 years of experience in engineering design, encompassing an extensive range of general building services, environmental passive design techniques, and the application of renewable and low-energy technologies.

David McAllister was the Project Manager at Arup, leading the SNFCC project from concept through to construction. As the lead MEP (mechanical, electrical, plumbing) engineer, David guided coordination between disciplines and steered the sustainability strategy.

More and more engineering companies, such as Siemens, are using virtual reality to make their manufacturing processes more efficient © Virtalis

HOW VIRTUAL REALITY IS CHANGING ENGINEERING

Far from being a technology of the future, virtual reality is now well established in multiple industries and sectors, ranging from entertainment, communications and education to design, scientific research and defence. Professor Anthony Steed, from the Virtual Environments and Computer Graphics group at UCL, explores how three companies are using immersive technologies to transform their engineering processes.

The UK has a long history of work in virtual reality (VR). In the 1990s, pioneering UK companies such as Virtuality and Division provided turnkey immersive systems to a wide variety of industries. While the hype died down and those companies faded away, over the past 20 years, pockets of use of immersive systems have emerged. In his 1999 'What's real about virtual reality?' article, published in *IEEE Computer Graphics & Applications*, Professor Frederick P Brooks Jr described a few examples of the two 'traditional' engineering uses of VR: design review and vehicle training. In that era, with high-end VR systems costing hundreds of thousands of pounds, the investment could only be justified in situations where the training would otherwise be very dangerous, or there were well-understood cost savings to be made in the design process.

Since the late 1990s, desktop computers have become capable of handling much more complex three-dimensional (3D) models and processing. Over the past two years, a watershed has been crossed where high-end desktop computers are now capable of driving real-time graphics at the speed required to enable a low latency experience in an immersive system.

At the beginning of 2017, Samsung announced that it had shipped over five million GearVR devices to convert its high-end smartphones into head-mounted displays. This type of display, and similar displays such as Google Cardboard, allows users to be immersed inside a computer-generated image. By turning their heads, they can experience a virtual scene as if it was surrounding them. More advanced systems such as the HTC Vive and Oculus Rift add motion tracking of the head-mounted display and handheld tracking devices, which allow the experience to be much more interactive. Having motion tracking enables the user to move around and use their hands to interact, and combined with appropriate software, this enables the user to experience the virtual scene as if it were real. This style of user interface, where the user employs their own motions, is easy to learn and very flexible; the user can at least attempt to interact with the objects that they hear and see in a similar way to the real world.

The fact that the virtual scene can be modelled on both the appearance and behaviour of real scenes suggests obvious routes for exploitation for engineering. While simulation and visualisation have long been tools that engineers have used, VR promises to make these technologies even more accessible to them.

ENHANCING DESIGN EFFICIENCY

Jaguar Land Rover has used immersive VR since 2006, employing the technology to design cars more efficiently. Brian Waterfield, Virtual Reality and High-end Visualisation Technical Lead, initiated a project to build a state-of-the-art CAVE-like display, an immersive virtual environment in which users stand in a small room where the walls are displays. It has stereo imagery (two views of the same scene, side by side) on four walls at 4K by 4K resolution (ultra-high definition). Although the displays are not head-mounted, the user still has to wear a pair of glasses to separate the views for their left and right eyes. Similar to a head-mounted display, the images on each wall can be drawn in a first-person point of view, so that the user sees 3D objects that appear to be inside

A 3D model of a Range Rover Evoque in Jaguar Land Rover's CAVE-like display. The computer simulations allow engineers to visualise full-size 3D models of components and the vehicle before physical parts are available
© Jaguar Land Rover

Attendees at the launch of the Jaguar I-PACE concept were able to have a multi-user experience using a set of HTC Vive head-mounted displays. Modern consumer head-mounted displays use screens similar to those in smartphones. They use lenses to create the impression that the screen's image is at roughly arm's length © Jaguar Land Rover

the display, and they can walk around and duck as they would do in the real world (although without the risk of banging their head).

In 2006, the displays, including the projectors and the 16 PCs needed to drive them, were a very significant investment. This spend was justified for a specific problem: designing the 'packaging' of a new vehicle. This is part of the early design process where the interior spaces of vehicles are laid out and tested for ergonomic fit and utility, and where the design team needs to make judgements such as lines of sight out of the vehicle and reach for the controls. It also needs to address interactions between passengers and the driver, and how the vehicle users will interact with non-driving controls, such as the boot space.

Using VR, the team was able to give early feedback about the impact of new designs on the requirement for all-round vision; this was something that was hard to assess from plans and renderings alone. To enable this, Waterfield's VR team used software to set up a simple process for taking 3D models of vehicles from their PLM (product lifecycle management) software to the display. VR became a part of individuals' work, as well as playing a major role in weekly cross-team design reviews. As packaging is a part of the design where interaction and user assessment is extremely important, the CAVE-like display, given its size, reasonable resolution and very wide field of view, was a good fit for these requirements.

Jaguar Land Rover subsequently started to invest in VR in other areas. In 2011, it built a large powerwall display – an ultra-high-resolution display – that is used for two-dimensional images and to aid visual design decisions. The company also invested in a high-end head-mounted display and an accurate large-scale system to track the user's body. This enabled assessment of manual interactions with the vehicle, including testing assembly and maintenance procedures.

With the release of low-cost consumer VR, more teams across Jaguar Land Rover are now looking at using it in their processes. Most visibly, a consumer VR experience was part of the launch of the Jaguar I-PACE concept, an electric-powered sports car. While several VR product visualisations exist, the novel aspect of this experience was that it was a social experience between HTC Vive head-mounted displays across the globe. More than 300 guests at the launch event were transported into a specially created virtual space where they watched projections of the car's creators, could interact with each other, and put themselves in the concept, 'sitting' on its virtual seats and having it built around them.

MODELLING BUILDINGS

Modelling in 3D has been a ubiquitous tool in many engineering disciplines for decades; the design, construction, and use of buildings and infrastructure is one such area where 3D models have had very broad impact. However, access to 3D models still requires that the users have the skills to interact with the model and interpret the images that they see. Global engineering consultancy Arup has been using real-time 3D models within its design and engineering processes since 2001. The use of these has constantly changed and evolved the organisation's practice through new graphics technologies and VR.

In 2001, Arup started implementing real-time visualisation of 3D models, which were generally commissioned by certain clients as a way to explore design issues. Traditionally, visualisation was achieved with static renderings and fly-through videos, but the addition of an interactive element introduced new

A prototype tool from Arup being used with a joystick interface to test the proposed signage at a large new underground rail station. The screens offer an accurate and realistic representation of the architecture and of a passenger's field of vision as the user walks through the virtual station. The lines of coloured spheres are traces of other virtual users, with colouring of the spheres indicating walking speed © Alvise Simondetti, Arup

opportunities. Alvise Simondetti, Global Leader of Virtual Design at Arup, explains that basic computer game software was used to create virtual walkthroughs of sites. The ability to walk through models was helpful in consultations with stakeholders, as elements that are hard to convey on video, such as crowd movements, could be visualised. However, moving models from a computer-aided design (CAD) format to the game software platform proved to be time consuming and involved remodelling original parts so that they would work in real time.

In later projects, such as Arup's redevelopment work on King's Cross Station, real-time 3D models became much more important for interdisciplinary working. For example, Simondetti recounts how a 3D model of the new Western Concourse was used in areas ranging from design of the CCTV coverage through to the marketing of the commercial restaurant units. In this and other station models, one interesting use of VR that had significant impact was the investigation of crowd movement. In trials, users could explore station models to follow routes that were expected to be challenging. A maximum journey time between any two points in the station had been agreed and the records of paths that users took around the models in VR could be used to examine potential design problems, such as congestion caused by missing, misplaced or contradictory signage.

More recently, Arup is exploiting new 3D technologies. Its work on High Speed 2 is using interactive visualisation to enable engagement with stakeholders, the media and the public. Because of the complexity and extent of the planning involved in the project, a 3D model has been built that integrates birds-eye-view navigation (similar to Google Earth) and panoramic footage where real photography has been augmented with renderings of the future line infrastructure. The combination allows a non-specialist to access the very large model quickly and easily.

TRANSFORMING FACTORY PROCESSES

As a relative newcomer to VR, in 2014, Siemens invested in display systems at its

The Virtalis ActiveWall at Siemens' Congleton factory allows a group of operators, designers and engineers to work together when developing workcells for the assembly line © Virtalis manufacturing facility in Congleton, Cheshire, where it designs and manufactures variable speed drives for motors. Its customers come from a variety of sectors, including automotive, machine building and the airport industry. A key part of the work carried out at the factory is the design of individual workcells to manufacture a new product, which can be a costly and time-consuming process.

Anil Thomas, a transformation manager at Siemens, explains that the process for designing a new workcell or revising an old design takes 12 weeks. A key part of this is when operators from the assembly line meet designers and engineers for an intensive five-day design session. The team previously interacted by using sketches or building physical cardboard prototypes, and VR was brought in to make this process leaner and more efficient. The company invested in an ActiveWall system, designed by VR specialist Virtalis, which comprised a large, wide projection wall and a floor. While less common than the CAVE-like display format used by Jaguar Land Rover, the ActiveWall allows groups of up to 10 people to work together in the immersive space and collaborate more easily. It is also of sufficient size to show a typical workcell at one-to-one scale, and be able to look down onto the working surfaces.

A high-end head-mounted display, which can be used by another person in parallel to the ActiveWall, also enables the designers to investigate reach and interaction around and between workcell operators, as some require one person to feed material and another to operate tools. As well as removing the need to build a physical prototype, VR has improved the quality of the design process, and Siemens is keen to introduce it to more of its process engineering and assembly to test whole factory performance.

THE FUTURE FOR VR

Despite the opportunities demonstrated, engineering is still a challenging area for VR, as engineering models are large and complex. Much of the content for the first wave of consumer VR has used simple models of cartoony appearance or panoramic video, because the use of a head-mounted display requires reliable, high frame rates so that users do not get disorientated when making rapid head movements. Over the next three to five years, as graphics cards to operate VR become cheaper, higher-end cards will be able to drive very large models of millions of polygons with complex lighting and shading.

Aside from an improvement in computing hardware, significant improvements in consumer head-mounted displays can be expected, with potential developments such as built-in eye-tracking to enable gaze-dependent rendering and social interaction, or a head-mounted display with 4K resolution in each eye. Although consumer devices are driving the acceptance and visibility of the technology, there is ample room for a high-end VR industry, supporting systems with higher display and tracking quality and new input modalities.

Powerwall and CAVE-like displays that allow multiple users to simultaneously experience VR will also have a place. There are prototype consumer room-scale projection systems, such as Razer's Project Ariana projector prototype shown at the Consumer Electronics Show (CES) 2017, which should enable large-wall interaction at a much lower price. A slightly different technology trend is mixed-reality where VR is combined with video to enable interaction between multiple headsets within a workplace.

Aside from the hardware systems, there are several software engineering challenges left to tackle. VR addresses user input and output, but so far there are no standards that enable easy integration into other software stacks. Over the next couple of years, initiatives such as WebVR application programming software and efforts of bodies such as the Khronos industry consortium should allow it to be supported within standard web stacks. This will greatly simplify the integration of VR in larger systems.

It is clear that engineering is a field where VR is already making a huge impact. In general, it allows access to situations or simulations that would otherwise be difficult to visualise or inaccessible to anyone except the specialists involved. By realising a virtual model, communication and interaction with designs and processes is made more efficient. Over the next two years, consumer technology should begin to meet the needs of engineering. There are a number of opportunities for companies to innovate in this area through software that combines established engineering tools with the new interactive opportunities of VR.

BIOGRAPHY

Professor Anthony Steed leads the Virtual Environments and Computer Graphics group in the Department of Computer Science at UCL. His research area is real-time interactive virtual environments, with particular interest in mixed-reality systems, large-scale models and collaboration between immersive facilities. The group runs a CAVE-like facility and several other high-end virtual reality systems.

FUTUREPROOFING THE NEXT GENERATION OF WIND TURBINE BLADES

The facilities at the Offshore Renewable Energy Catapult are used to carry out tests on wind turbine blades up to 50 and 100 metres © HR ORE Catapult

Before deploying new equipment in an offshore environment, testing is absolutely vital. Replicating the harsh conditions within the confines of a test hall requires access to specialist, purpose-built facilities. Kirsten Dyer, Research Materials Engineer, and Peter Greaves, Research Structural Engineer (Blades), from the Offshore Renewable Energy Catapult discuss the challenges facing longer blades and how testing can help reduce the time and cost of manufacturing.

The current generation of offshore wind farms being deployed around the world are bigger and more efficient than ever before. The first offshore wind farm, Vindeby, was installed in Denmark in 1991 and comprised turbines of 450 kW (kilowatts) with blades 16 metres long. Since then, turbines have advanced considerably, with machines now that are 8 MW (megawatts) and over. Manufacturers are increasingly designing larger, more effective models that are contributing to cost reductions in offshore wind. As a result, bigger turbines need longer blades, with current manufacturers designing and testing blades up to 88 metres long. However, such an increase in scale carries associated physical and environmental engineering challenges that the industry must address.

Longer blades present engineering challenges around blade design, materials and condition monitoring. Wind farm owners and operators need to design longer blades that can survive in the harsh offshore environment, and at the same time improve their understanding of issues such as behaviour in real-world conditions, erosion and remedial repair requirements as the assets age.

As the UK's flagship technology innovation and research centre for wind, wave and tidal energy, the Offshore Renewable Energy (ORE) Catapult is helping to tackle these challenges through a combination of engineering expertise, industry collaborations, and its test and demonstration facilities.

THE BENEFITS OF BLADE TESTING

ORE Catapult's 50 metre and 100 metre facilities are used to carry out industry blade tests, and its 7 MW (megawatt) Levenmouth demonstration turbine is used for blade research and development. This approach to industrial research and development, and the employment of representative testing, can bring many benefits to equipment manufacturers, asset owners and investors. This helps to reduce the cost of unplanned maintenance and increases availability and output. Design margins can be reduced, saving costs on materials and contributing to more efficient designs. The iterative design process is accelerated, which can reduce the time and cost of getting a new technology to market.

CHALLENGES FOR LONGER BLADES

As blades get longer, the most severe structural load cases change during rotation meaning that the fundamentals of blade design also have to change. For example, self-weight from gravity loading and the torsional stiffness of the blade become more significant. However, by minimising the increase in weight as the blade gets longer, the change in stresses is reduced. Two factors are key in reducing the weight of longer blades: more efficient composite design, which can be achieved by using materials with high strength-to-weight ratio; and the development of better manufacturing methods, resulting in reduced defects in the blade, and therefore increased strength.

In terms of blade materials research, offshore environmental conditions are very poorly characterised. No databases exist of detailed temperature, humidity, ultraviolet (UV) and rain droplet size distributions data in the offshore environment for rotating equipment. Instead, data is transferred from that collected by oil and gas platforms. The effect of this missing data is that current accelerated coating, weathering and rain erosion tests may not be appropriate and may explain, in part, the difference in the performance of blade coatings during accelerated testing, compared with actual performance in real-world conditions.

The phenomenon of blade leading-edge erosion is a significant one for the offshore wind industry. The erosion of the leading part of the turbine blade – the part that experiences the strongest impact of rain droplets and other airborne particulates – is a problem both on- and offshore, but the erosion seems to be accelerated offshore because of the harsher environmental conditions. Erosion affects the aerodynamic performance of the blade by reducing the amount of lift the blade generates and increasing its drag. It also affects structural integrity as water entry and UV (ultraviolet) light exposure can lead to structural damage. This can result in reduced turbine efficiency, reliability and availability, and increased operations and maintenance (O&M) activity, with repairs in situ being difficult and expensive. All of this proves

ACT BLADE

ORE Catapult is working with Edinburgh-based SME ACT blade to develop and test next-generation engineered textile wind turbine blades.

After responding to one of ORE Catapult's innovation challenges, the team worked with engineers from yachting design specialists SMAR Azure, which resulted in the spin-off company ACT Blade. The aim was to study the feasibility of adapting the sail modelling technology into modular blades that are over 50% lighter than those in use today.

Put simply, a lighter blade can achieve greater power production. If a blade is lighter, it can be made longer than the current 55 metre standard. In turn, the longer blade captures more wind and increases energy production, which lowers the levelised cost of energy (LCoE).

Made up of an internal composite structure and high-tech textiles, as opposed to the prevailing fibreglass, ACT Blade's design has the potential to reduce the levelised cost of offshore wind by 8.7% while increasing energy production by 9.7%.

The development of modular blades also has implications for developing countries, where poorer infrastructure means full-length blades are all but impossible to transport. There are environmental advantages, too: while glass-fibre blades are landfilled at the end of their working life, ACT Blades will use recycled carbon fibre.

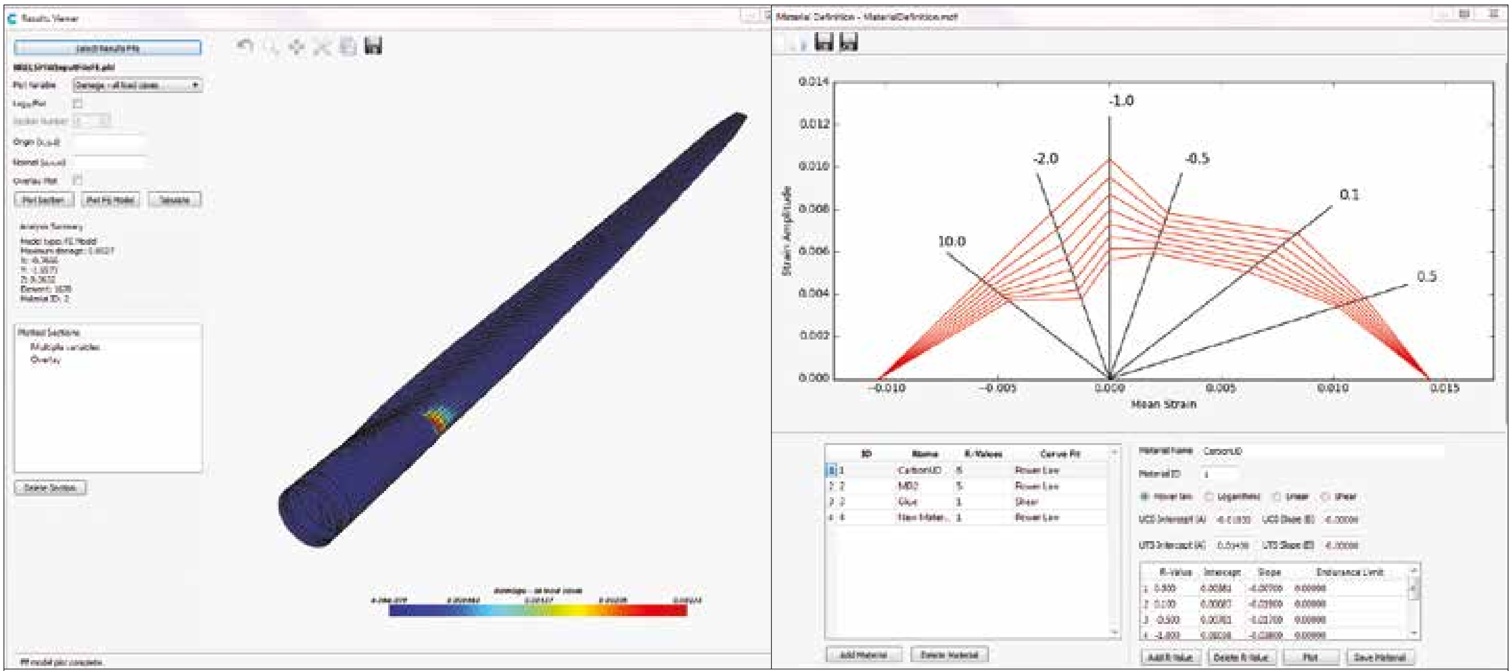
After helping ACT Blade to secure several rounds of investment, ORE Catapult is developing a new test rig at its facility in Blyth to validate and demonstrate a section of the blade.

Blade leading-edge erosion is one of the key challenges facing the offshore wind industry. Leading-edge erosion is accelerated offshore because of harsher environmental conditions and can prove costly for offshore wind farm owners and operators, through lost power generation and revenue

costly for offshore wind farm owners and operators, through lost power generation and revenue.

New coatings are now coming to market that have significantly improved performance in accelerated rain erosion testing. However, good performance in accelerated testing has not always translated into good in-service performance, because of a lack of understanding of the many factors that affect blade erosion. These factors include the test method itself and a lack of understanding about the erosion damage mechanisms connected to material properties. This can be caused by a lack of analysis techniques that can cope with the very high-strain, high-frequency environment, a lack of understanding of offshore conditions, and insufficient research into the interactions between the blade structure and the coating layers, and how they are affected by, for example, the application process and blade manufacturing.

ORE Catapult's blade leading-edge erosion programme aims to better quantify the magnitude of leading-edge erosion across



Outputs from the blade fatigue simulation software, developed by ORE Catapult in partnership with Durham University, and certified by DNV GL. The software certification provides vital assurance that the results that the new test method generates will conform to industry standards and guidelines

the sector by investigating its effect on wind turbine blade efficiency, assessing the impact on aerodynamic performance and structural integrity and on the overall cost of electricity generated from offshore wind. One programme objective is to minimise O&M activities while maximising reliability and availability, thereby cutting the cost of electricity generated from offshore wind.

Once blade damage occurs, repairs are generally carried out in situ: by crane access onshore and by rope access offshore. The biggest issue surrounding blade repair is environmental conditions: UV radiation, temperature and humidity can affect the resins and fabrics used during the process and potentially reduce the quality of the repair. New repair materials with wider application conditions are required, as well as new curing techniques to apply heat in situ during rope access. For blade leading-edge repairs due to erosion, the quality of the repair affects the performance of the repair leading-edge coating.

BLADE TESTING

Before blades are deployed in the field, manufacturers use blade test facilities to prove, validate and de-risk their new technologies to improve investor and customer confidence. This can be a long and expensive process, and is not always representative of how blades operate in real-world conditions. The number of test halls capable of carrying out very long blade tests is also limited.

In preparation for testing, wind industry-specific simulation software is used to determine the loading that wind turbine blades can expect to experience in real-world conditions. This software takes into account how the turbine structure moves when mechanical loading is applied to it. Loads arise from the wind, waves, tides, and the wind turbine control and electrical systems.

Thousands of scenarios (or ‘load cases’) are simulated and wind turbine design standards dictate the conditions that the turbine will see in each load case. Once these simulations have been performed, the extreme values of the loads at a series of points along the length of the blade are determined. Safety factors are applied to these loads to account for the fact that the turbine may see greater loads in service than in the simulations. These extreme values form an ‘envelope’, and are described by a maximum and minimum value in each direction.

The everyday loading that the wind turbine will see is also simulated. These simulations might include, for example, the turbine operating at different wind speeds, the turbine starting up and shutting down, and the turbine in a parked condition when the wind is either too light or too strong for it to operate. These load cases form a subset called ‘fatigue’ load cases, and are analysed in a different way to the extreme loads.

A fatigue analysis takes into account how the strength of the materials used in the blade will decrease over time because of repeated loading. Imagine bending a paper clip: it will not break the first time you bend it, but if you continue to bend it back and forth then eventually it will snap. The goal of a fatigue analysis is to ensure that although the blade will go through perhaps 100 million loading cycles during its lifecycle, it will still have plenty of life left after 25 years of operation.

STATIC AND FATIGUE TESTING

Wind turbine blades are type tested, meaning that each new design, or any substantial alteration to an existing design, is validated. Full-scale blade tests are performed by bolting the blade to an extremely strong, fixed concrete hub so that they are cantilevered out horizontally. Loads are then applied to the blade to ensure that it can survive the loading that was calculated at the design stage.

Wind turbine blades have

two main sources of loading: aerodynamic loading from the wind, and gravity loading caused by their own weight as the blades spin. The aerodynamic loading acts mainly in the 'flapwise' direction. If you think of a blade as being like an aeroplane wing, then the flapwise load would act to move the blade up and down. The gravity loads act mainly in the edgewise direction; in the plane wing analogy, they act to move the blade forwards and backwards. Blade tests are primarily designed to ensure that the blade can survive loading in these two directions.

In a static test, the blade is loaded using between five and eight winches at a series of points along the blade. The winches are attached to the blade by wooden clamps that fit snugly around the aerodynamic profile of the blade, and loads are applied to the blade in four directions: flapwise maximum and minimum, and edgewise maximum and minimum. The winches stay in the same place for these four tests and the blade is rotated about its long axis. The loading is calculated in such a way that the blade undergoes more extreme loading in each direction at each point than was calculated in the simulations.

After the static tests, the blade is fatigue tested. This test involves exciting the blade at its natural frequency so that it undergoes several million cycles. The loads are calculated so that the blade is subjected to an equivalent amount of damage as it will experience during its service life.

BI-AXIAL TESTING

ORE Catapult is addressing the challenge of reducing the time and costs of blade testing, and making it more representative of real-world operating conditions, by developing a bi-axial testing method. This joint industry and academic collaborative approach to designing the bi-axial testing methodology aims to reduce fatigue test times by almost a half, and overall test times by up to 25%.

However, testing bi-axially is not as simple as applying the single axis test loads at the same time. This would produce an extremely conservative test that would damage the blade much more than its service life. This is because, in service, the flapwise loads are mainly aerodynamic and the edgewise loads are mainly driven by gravity. The aerodynamic loading varies as the rotor spins, with a maximum load reached when the blade is at the top of its cycle (because the wind tends to blow faster higher up, a phenomenon called wind shear) and a minimum when the blade is at the bottom of its cycle (when it passes through stagnant air in front of the turbine tower). This means that the gravity loading lags behind the aerodynamic loading by 90°, which tends to drive the tip of the blade in a curve.

During a bi-axial test, in which both axes are excited simultaneously at their resonant frequencies, the blade will regularly experience combinations of loads that would not occur in practice because the flapwise and

WIDEBLUE

ORE Catapult is working with Wideblue – formerly Polaroid's R&D lab – to develop its optical technology into a sophisticated digital image correlation system that can detect blade deformation.

The Blade Optical Health Monitoring (BOHEM) project will develop a low-cost, optimised, optical condition monitoring solution for blades that can be used during the development of new designs and in the operational field.

During the first phase of the 12-month project, Wideblue's sensing technology will be applied to ORE Catapult's research blade to learn more about its capabilities. It will then be deployed on the 7 MW Levenmouth demonstration turbine, where it will undergo trials in a real-world, operational offshore environment. The data generated will be used to monitor individual blade health, allow early detection of any changes in performance, instruct more effective maintenance and allow for better justification of life extensions.

Optical condition monitoring takes place inside a wind turbine blade, using the digital image correlation system developed by ORE Catapult and Wideblue

The 7 MW Levenmouth demonstration turbine provides training and development of skills vital for the future of the offshore wind industry. Researchers can develop a deeper understanding of a wide range of technologies as well as the operations and maintenance aspects of offshore wind turbines, with the ultimate goal of reducing the cost of energy

edgewise frequencies are very unlikely to be exactly the same – the tip of the blade will be driven in what is called a Lissajous curve.

ORE Catapult has addressed this problem by moving away from the conventional method of fatigue testing (which involves calculating test loads and then counting the number of cycles that the blade undergoes) in favour of monitoring how the theoretical damage is accumulating during the test. This means that the test loads do not need to be rigidly held at a given level, which is impossible when testing bi-axially because the flapwise and edgewise modes interact, and also allows the combination of fatigue tests to be optimised to match the damage that the blade is predicted to undergo in service.

The test method is dependent on knowing the theoretical fatigue damage that the blade would experience in service. For this reason, ORE Catapult has developed sophisticated wind turbine blade-specific fatigue analysis software that has been certified by DNV GL, a technical assessment, advisory, and risk management body. An accurate fatigue analysis has very tangible benefits, as it allows a substantial reduction in material strength safety factors. Compared to the more simplistic analysis, the software enables the user to reduce material safety factors by a factor of two – this could potentially have significant implications for the amount of material required to produce the blade.

Once a fatigue analysis has been performed to assess the service life damage, the result is fed into an optimisation routine. This aims to tune the flapwise and edgewise mode shapes (by altering the position and mass of the test equipment on the blade) so that the test loads cause damage that matches the service life damage over as much of the blade as possible.

With the test design complete, the blade test can begin. Strain gauge data from the blade test is processed into a format that can be read by the fatigue analysis software. This makes it possible to compare the damage subjected during the test to the predicted service life damage, which can then be presented to a certification body to demonstrate that the blade has been thoroughly tested.

After the fatigue tests, the static tests are repeated. This demonstrates that the blade can still survive the extreme loads, even if they occur at the end of the turbine's lifetime.

The development of a bi-axial method of testing has attracted interest from industry, including a collaboration with international blade manufacturer LM Wind Power. The collaboration aims to reduce the cost of offshore wind by designing, validating and deploying the world's largest offshore wind turbine blade. At 88 metres long, the blade will undergo bi-axial testing and – it is hoped – will achieve a significant reduction in the levelised cost of energy by means of lighter construction and a more predictable operational expenditure through reliability-driven design. ORE Catapult will test the blade in its 100 metre facility, alongside the continuation of its work on the issue of blade leading-edge erosion.

BIOGRAPHY

Kirsten Dyer is ORE Catapult's Senior Research Materials Engineer and is responsible for developing products, services and solutions in the area of materials on blades for the wind and tidal sectors. She previously worked for Gamesa and BAE Systems.

Peter Greaves is a Research Structural Engineer (Blades) for ORE Catapult. He graduated in 2006 from Newcastle University with a degree in mechanical engineering and then studied for an MSc in renewable energy. ORE Catapult funded Peter's doctoral studies on bi-axial blade fatigue testing.

GOING FOR GOLD

Great Britain's women's team pursuit wins gold in the velodrome at the Rio Olympics and breaks the world record © Simon Wilkinson/swpix.com

The success of Great Britain's cycling team at the 2016 Rio Summer Olympic Games was, quite rightly, celebrated and athletes such as Laura Trott CBE, Jason Kenny CBE and Sir Bradley Wiggins CBE entered the record books. But what about the closely guarded technology that contrabuted to their success? At an Institution of Mechanical Engineers' event held at the University of Cambridge, Professor Tony Purnell, British Cycling's Head of Technical Development, spoke about the engineering approach taken – although he couldn't share any secrets.

After the 2016 Summer Olympics in Rio de Janiero, Brazil, the British Cycling team returned to the UK having won 12 medals – six of which were gold. The team once again dominated the Olympic sport and the press speculated about what had led to its success, suspecting secret skinsuits and aerodynamic paint, among other things.

The press was right to wonder if engineering had made a significant impact. Professor Tony Purnell, Head of Technical Development at British Cycling, points out the striking difference in the way the 1,500-metre record for running and the four-kilometre team pursuit cycling world record have changed over the last 30 years. Both events are nominally around four minutes, but the 1,500-metre record has hardly changed, while the cycling time has dropped by some 13 seconds. Calculations that Professor Purnell made revealed a need for some 15% improvement in power or about 17% less aerodynamic, rolling and friction drag reduction to improve on this time. A combination of factors led to the success of the British Cycling team in Rio, but it is clear that engineering played a key role.

FUNDING RESEARCH

British Cycling receives a grant from the National Lottery (it received £30 million in the four years leading up to Rio) and a portion of this is invested in research and development led by Professor Purnell.

Following a career in technical development for Formula One, Professor Purnell joined British Cycling in 2013 with a job to "employ technology in any way I can to make the Olympians faster". With improvements being made not only by Team GB, but by other countries' teams as well, to record the fastest possible times, the focus was on marginal gains that could be made to improve performance. "Some of the races are very close and if you can make the slightest difference to push your rider in front, it can be the difference between gold and silver," Professor Purnell explains.

Before focusing on the areas where these gains could be made, Professor Purnell used mathematical modelling to work out how a 1% improvement would affect the changeable variables:

- rider power
- total mass
- frontal area
- coefficient of drag
- coefficient of rolling resistance
- inertia of wheel
- drivetrain efficiency.

A finite element analysis (FEA) process was used to aid development of the T5GB frame. The T5GB achieves part of its performance benefit by having a shape that reduces aerodynamic drag. However, this reduction runs counter to the need to have frames that are structurally optimised for high stiffness and low weight. One of the advantages of the T5GB is that it incorporates those two contradicting requirements. This balance was achieved by using technical expertise and experience from motorsport and similar high-tech/fast-paced industries to engineer the optimal frame in a rapid timescale © Lentus Composites and Cervélo

Within these variables, Professor Purnell and his team decided to focus their research on frontal area, coefficient of drag and drivetrain efficiency as these were the areas where a small increase in percentage could make the biggest gains in speed.

In preparation for London 2012, the team of engineers working with British Cycling (known as the 'Secret Squirrel Club') had made a lot of progress and modified the obvious engineering on the bikes but more research was needed in order for it to continue. Professor Purnell realised that funding would not stretch to research and to build a new bike so, as a Visiting Professor at the University of Cambridge, he decided to "shamelessly exploit the ability and enthusiasm of Cambridge students" to carry out research. A group of engineering students, studying Master's, PhDs and carrying out postdoctoral research, worked on projects that included turning the velodrome into a wind tunnel, measuring rolling resistance, optimising the changeover timing of the team pursuit, aerodynamic handlebars, testing the stiffness of the bike frames and investigating whether cyclists should shave their legs. "The students were really good at investigating whims,' explains Professor Purnell, "and once we were fairly confident we could make a gain, we then went to consultancy services."

A NEW FRAME

The most visible outcome of this research was the development of a new bike frame by racing and track cycle specialist Cervélo, which was supported in the engineering and manufacturing of the new frame structure by Oxford-based engineering firm Lentus Composites. Development of the frame began 18 months before Rio and it was the ability of the British company to develop parts at a high quality and such a rapid speed that made the project possible in such a short space of time.

The British Cycling team had previously used the UKSI frame in the Beijing and London Olympic Games; however, for the Rio Games, Cervélo had designed a new shape – the T5GB, which was more aerodynamic than the UKSI. Lentus Composites' task was to manufacture this new frame but ensure that it matched the stiffness and lightness of the previous bike, and passed all of the International Cycling Union's (UCI) stringent safety and strength tests. A carbon-fibre reinforced polymer composite frame, the T5GB is made from a mixture of several different kinds of carbon that offered certain properties in terms of either stiffness, weight, or toughness, materials that offer properties that exceed high-performance steel, but at a fifth of its weight. The frame was first built as a 3D finite element analysis (FEA) mesh and simulated more than 50 times to optimise stiffness, weight and safety. Specialist

HOW ENGINEERING HELPED

The most visible technology improvement delivered by the research was the Cervélo T5GB track bike. While people may have looked at the equipment and expected to see something dramatically different, in reality the devil was in the detail. The prototype of the new bike was made from 3D-printed plastic and tested in a wind tunnel. The figures were very encouraging from the start, reflecting Cervélo's long specialisation in aerodynamics. When built up into a complete bike without a rider, it produced over 10% less drag when tested back to back. Further tests added a pedalling rider adopting the sort of position that an Olympic rider would take in the various events. This showed a solid gain in excess of 1%, which was seen immediately when the bike started to undergo track tests. "People forget that wind tunnel testing is a simulation, not the real thing, so the track testing programme was important to us as it gave concrete evidence for performance gains or losses," adds Professor Purnell. The track tests confirmed the observations of the previous experiments. "One percent does not sound that much, but when one feeds this into British Cycling's computer simulations it gives the team pursuit about 0.8 seconds gain over the four minutes or so of the event. That is around a 15 metre gain, which funnily enough is about how much the British men beat the Australians by in the final."

Left: Engineers place computer-cut plies into the mould tooling, based on the design that was developed through the FEA process. The placement of these plies is critical to achieving the desired frame stiffness and strength, so they have detailed instructions and diagrams to help. Right: An engineer tests the finished frame for stiffness at Lentus Composites. Multiple stiffness tests were carried out using methods that were developed by Cervélo, based on its knowledge of how frame stiffness relates to bike performance and rider feel. The test demonstrates that the T5GB will behave and handle in the way Cervélo intended
© Lentus Composites and Cervélo

software was used to cover the mesh in plies of composite (moulded layers), allowing the bike to be built in a virtual environment and put through the same stiffness tests as the real frames would be. While this was ongoing, a number of development bikes were built and tested to validate the FEA process.

Using the same software, the engineers were able to generate the two-dimensional ply shapes needed to cut out the materials at a later stage and model how the fibres would lay in the final frame, an important aspect that was key to the resultant performance. When it came to manufacture, the engineers were faced with 120 flat shapes of all different sizes and materials that needed to be laid onto the frame in the correct order and location to generate the required properties. Once that was complete, the bikes were covered in a paint that was lighter than clear lacquer. The paint, and the process of applying it, was specially developed by a separate firm for use in ultra-lightweight liveries on composite materials. Its use on the T5GB was the world's first application of the technology.

The computer-aided engineering process was integral to the overall design and allowed Cervélo and Lentus Composites to deliver a bike that worked the way British Cycling needed it to in the time available, rather than having to build and test multiple frames.

As well as the changes that were made to the bike frame, the team focused on coefficient of drag by making improvements to the handlebars, shoes and skinsuits – "just about anything that could give us an advantage," Professor Purnell adds. This included a focus on riders refining their positions to gain aerodynamic advantages.

All of the changes and improvements made were rigorously tested before being implemented and Professor Purnell is keen to point out that there was a big emphasis on evidence-based decision making. "Quite close to the games, we began to doubt some tyres that had been ordered so a couple of students spent two days testing them on a rolling rig in the lab," he explains. "They fell to pieces rather too quickly so we had to change them at the last minute. If that testing had not have happened, we may have gone to Rio with the wrong tyres."

TEAMWORK

Approaching Rio, the velodrome at British Cycling's training facility was covered in instruments and cameras so that the technical team could arm the coaches and riders with hard facts and evidence rather than opinion. There was always the worry that the coaches and riders would think of Professor Purnell's team as "hair-brained boffins who weren't going to deliver anything", so it was gratifying to first see the women's team pursuit and then the whole squad embrace the approach to help improve their times.

Undoubtedly, the work of the technical team and the coaches and riders paid off. The women's team pursuit first broke the world record in the qualifying rounds for the World Cup in Manchester in 2013 with 4:23.910, and continued to break them until setting a new world record of 4:10.236 in the finals at the Rio Games in 2016 – winning gold, of course.

However, the team's work did not end with Rio. As Tony says: "Is there more to come? We'll have to wait until the Tokyo games to answer that."

BIOGRAPHY

Before taking up the position of Head of Technical Development at British Cycling, **Professor Tony Purnell** spent more than 10 years working in Formula One. He is a Visiting Professor at the Department of Engineering at the University of Cambridge and a Fellow Commoner of Trinity Hall College at the university.

Graeme Hyson is a Lead Engineer at Lentus Composites, an engineering-led manufacturer of composite products, assemblies and systems for a range of industry sectors. Graeme presented the frame engineering process at the talk.

FORGING LINKS BETWEEN ACADEMIA AND INDUSTRY

After 10 years as Vice-Chancellor at Aston University, Julia King, Baroness Brown of Cambridge DBE FREng, took on the role of Chair at the new Sir Henry Royce Institute for Advanced Materials at the University of Manchester in 2016 © Robert Taylor

For Julia King, Baroness Brown of Cambridge DBE FREng, materials science has been a common theme in a career that has taken in the academic world at all levels, along with time in the higher echelons of corporate engineering. She talks to Michael Kenward OBE about her current enthusiasms and concerns.

In her journey from a West London girls' school to the House of Lords, Julia King, Baroness Brown of Cambridge DBE FREng, has taken a far from typical path. She started on a traditional academic route, studying A levels in science and then natural sciences at the University of Cambridge, where she quickly abandoned thoughts of becoming a particle physicist. "When I got to university, I realised that I was much more interested in the problem-solving bit," she says, so when looking for a PhD project, Baroness Brown turned to materials research, in particular fracture mechanics.

That PhD could have been the beginning of a traditional university career, ascending the academic levels to the heights of vice-chancellor. Baroness Brown did get that far, running Aston University between 2006 and 2016, but her journey there was varied. She started with 16 years at Nottingham and Cambridge universities, followed by almost a decade as a senior engineer with Rolls-Royce, before going back into academia.

MAKING CONNECTIONS

Baroness Brown's links with Rolls-Royce date back to when she completed her PhD at the University of Cambridge and stayed on as a Rolls-Royce Research Fellow. She then joined the University of Nottingham as a lecturer. Most of her research students were "working on real problems and solutions to them" sponsored by industry, including Rolls-Royce. Her growing reputation in materials research led to her appointment as the Royal Academy of Engineering's first Senior Research Fellow, supported by British Gas. Baroness Brown may have left Cambridge by this time, but her old colleagues had not forgotten her; a letter arrived inviting her to move her fellowship and her research team back to the university.

Reinforcing her contact with Rolls-Royce, it was around this time that the company was rethinking its approach to research, especially its university links. It decided to concentrate on bigger teams in a smaller number of groups, in what it dubbed University Technology Centres (UTCs). Rolls-Royce invited bids when it wanted to establish a UTC in nickel-base superalloys. The University of Cambridge won and Baroness Brown took on the task of establishing the new UTC.

It was not long before Frank Litchfield, the then director of component engineering at Rolls-Royce, invited himself to see the materials UTC. At first, Baroness Brown

Baroness Brown speaks at Aston University's 50th anniversary at the Cathedral Church of St Philip in Birmingham in September 2016 © Aston University

thought he wanted to check up on the academics. Instead, Lichfield invited Baroness Brown to "come and talk about a job", and this resulted in her joining the company as Head of Materials. Bringing in an outsider, albeit one familiar with the aerospace business, was, she says, "very rare". Rolls-Royce traditionally recruited engineers as graduate apprentices straight out of university and developed them through the company.

Some colleagues warned Baroness Brown that the move to industry could be a culture shock. "It was different," she says, "but it wasn't really a shock." However, she does admit to mild panic when her eye caught the 25 bound-volume 'quality system' that she was supposed to keep up to date. "I found that a mystery," she says with a laugh, "but quality was hugely important." The materials Baroness Brown worked on went into critical parts of aircraft, so Rolls-Royce had to be able to prove to the regulators that its products were safe. "It used to worry me that they would come and find that we weren't up to date with the quality manuals."

Baroness Brown also found that the company's engineers were not universally enthusiastic about what they saw as a move to outsource research, which they enjoyed doing, to the UTCs. As a result, they were not keen to act as go-betweens with the UTCs. They were also nervous about talking to academics about the company's problems, in case secrets got out to the rest of the world.

Baroness Brown could see that the quality of the interactions between the company and the UTCs depended on the quality of the people at the interface. She also understood that 25 years in a company can lead to "a kind of group think" and the notion that there was a Rolls-Royce way of doing things. "To solve some of the technical challenges we had, we did need people coming in with different ways of thinking and solving problems," she says. "We wanted the UTCs to stop us doing this 'group think' stuff that big companies are always in danger of doing."

A CHANGE OF ROLE

Two decades on, the university/industry picture is very different. Things have changed a lot, says Baroness Brown. "Back then it really was two cultures. In [university] engineering departments there is now much more understanding about what industry needs." Engineers in industry also have a better understanding that companies have to make profits. In the past, the company's materials people loved the idea of developing futuristic new alloys. However, from the company's point of view, says Baroness Brown, "looking for ways to increase the operating temperature and life of existing materials can have much a more immediate impact on profitability. The challenge was to get people from being most excited by their subject to being excited about delivering new products and making money."

The UTC system is now seen as a role model for companies working with universities, but challenges remain. "You have to work very, very hard at that interface all the time. We still haven't cracked this problem of getting more people to move between universities and industry." One suggestion, she says, is to have independent pensions that move with the worker. There are still some cultural differences between universities and industry. "But if there wasn't a cultural difference it wouldn't be worth doing the collaboration."

After eight years in various roles at Rolls-Royce, Baroness Brown followed her own thinking on moving between domains. She admits that leaving Rolls-Royce was a case of circumstances and an approach from a headhunter. With the appointment of a new Rolls-Royce director of engineering, she could see that she would not get that job any time soon, so in 2002, Baroness Brown took up the offer of a job in London to run the Institute of Physics.

That plan, working somewhere between the business and academic worlds, did not last long. In 2004, she was offered the job of Head of Engineering at Imperial College London. Then two years later, the headhunters called again and, in December 2006, Baroness Brown became Vice-Chancellor of Aston University.

She confesses that, apart from a fleeting visit to Aston to a conference as a research student, "it was not a university I knew very much about". Her impression of "a university in the middle of a motorway" changed when she discovered Aston's approach to widening participation of students from communities that usually shied away from universities. "That was one of the things that attracted me to it. It was a really pragmatic and capable institution that was absolutely committed to giving opportunities to people. It manages to combine that with some very good research." She is amused by the description of the university as delivering 'employable graduates/exploitable research', a slogan that prompted one publication to describe it as "one university that does what it says on the tin".

CHAMPION OF RESEARCH

Baroness Brown's time at Aston coincided with significant changes in how universities are judged. In particular, the Research Excellence Framework (REF), the series of research benchmarking exercises carried out every five or six years since 1986, added a new measure of excellence. For the first time, the Higher Education Funding Council for England, the body that ran REF2014, asked universities to explain the impact of their research ('Research with impact', *Ingenia* 69).

Baroness Brown describes herself as a fan of REF's impact assessment. "REF has been very helpful, particularly in science and engineering." It has also been helpful in getting other disciplines to think about how their work is valuable outside the academic setting. "It is good for all disciplines to think about their impact." She quotes work on forensic linguistics at Aston, where researchers are thinking about starting a company to help businesses to identify whether their communications are coming from the people they are supposed to be talking to, a relevant topic in these days of rising cybercrime.

In Baroness Brown's view, REF's database, which is getting on for 7,000 case studies, is a "fantastic resource" that companies, for example, can turn to in search of expertise. "The Engineering and Physical Sciences Research Council (EPSRC) has made really good use of REF," she says, but the rest of the research community could do more with this resource. "There is this huge richness of data that should be being more strongly used by government and others, companies as well."

Baroness Brown's interest in REF, and her membership of Lord Stern's review of the exercise, illustrates an increasingly important role for her as an active member, sometimes chair, of influential committees. She headed up the team that produced *The King Review of low-carbon cars* in 2008, a groundbreaking exercise, produced as a response to Lord Stern's review of the economic impacts of climate change, which was one of those rare documents that did not disappear with a change of government.

GREEN FOCUS

Baroness Brown's own interest in climate change has, if anything, become more pronounced. It influenced her work at Aston where, with some effort she admits, she persuaded the university to offer all second-year students a 'stop the year' week away from their courses, to work together on trying to reduce climate emissions. As Baroness Brown says, whatever they end up doing for a living, these are the people who will lead industry, universities and the other organisations that will have to adapt to the effects of climate change.

Climate change remains one of Baroness Brown's major preoccupations. She is a Non-Executive Director of the Offshore Renewable Energy Catapult (see pages 30 to 35), and is one of eight independent members of the Committee on Climate Change (CCC). "I really enjoy the work," she says. It gives her a chance to do something technical again, she adds.

Chaired by Lord Deben, the CCC provides "independent, evidence-based advice to the UK and devolved governments and parliaments", setting carbon budgets, for example. Baroness Brown admits that the CCC can face an uphill struggle in trying to promote responsible policymaking. She explains: "We know that flooding is going

For her 'company car' as Vice-Chancellor of Aston University, Baroness Brown opted for a small electric SMART car, which, when it was not being used for official business, was a big hit in visits to local schools where it helped to spread the message about climate change © Aston University

to become an increasingly problematic part of our weather variation and yet we are still building in places that will be susceptible."

Such issues will be a part of a fresh challenge for Baroness Brown as the new chair of the CCC's adaptation sub-committee, taking in areas such as farming and health as well as the more familiar territory of economics and engineering. Baroness Brown remains active in these domains in another new job, as a Non-Executive Director of the Green Investment Bank. Set up and backed by the government to promote investment in the UK's 'green economy', the bank has two key tasks: to deliver a financial return but also to deliver what she describes as "a green return". She interprets her job at the bank as addressing the question: "How you describe the green bottom line?".

A POLICYMAKER

The ability to turn back the floods may be beyond Baroness Brown's skills, but as a crossbencher in the House of Lords, she is far from powerless in policymaking circles. She naturally takes a close interest in higher education and has been leading the way in discussions in the upper house about the government's plans to change how universities operate in the UK.

The Higher Education and Research Bill sets out "to make provision about higher education and research; and to make provision about alternative payments [a student finance model that will be an alternative to a loan] to students in higher or further education". Among the various problems that Baroness Brown sees is the bill's lack of a definition of a university. Baroness Brown is not against changing universities, believing that some of the proposals will be good and will provide more choice for students. "It will give unconventional students much more flexibility in the degrees that they can acquire, but we do need to think hard about how we use the term university."

Baroness Brown illustrates her concerns with an example. A registered higher education provider with 150 students in an office block may well be able to run a good course, teaching one subject to a very high level. "But I don't think that is a university," adds Baroness Brown. As the bill now stands, she explains, it allows the government and the proposed Office for Students to decide what constitutes a university. "We should be involved in that," she says. "We should provide a checklist that says 'It is a university if…'. I don't think it is something that a civil servant can decide, without some strong guidance."

She also has concerns about the bill's possible impact on the fate of Innovate UK inside UK Research and Innovation, the new body that will bring it together with the research councils. She has submitted amendments to the bill to "strengthen a degree of independence for Innovate UK". Culturally, she insists, Innovate UK has to be very different from the research councils. Its role is not simply to exploit ideas from universities, she insists. It has to be free to look at investing, as well as providing grants and loans. "We need to ensure that it retains its independence and business focus beyond the current players. It interacts a lot with business directly. We need to preserve that and make sure that it doesn't get any harder."

For all her concerns about universities in the UK, Baroness Brown feels that "we worry far too much about higher education. We have good higher education. I get frustrated by the discussion that too many people are going to university, and that they should be doing apprenticeships." There is a lower unemployment rate among graduates. Forget about persuading those who do want to go to university to think about apprenticeships, and do something about the other 50%. "That will make more difference to us than trying to persuade people not to go to university."

Baroness Brown's interest in education also takes in younger students. She is "very passionate", a phrase she uses to describe many of her activities, about her role as chair of STEM Learning Ltd, a not-for-profit company that provides continuing professional development (CPD) for science teachers. "What we really need is for CPD to be compulsory for teachers," says Baroness Brown. It is not just necessary to refresh teachers' science knowledge and to introduce them to new ways of teaching, "it is also important to keep teachers motivated". Baroness Brown believes that money for this work should be a part of schools' budgets. "The cost of losing good teachers to the system is huge."

NORTHERN FUTURES

Baroness Brown's continuing interest in education and climate change does not mean that she has abandoned her original interest in materials and engineering. She is Chair of the new Sir Henry Royce Institute for Advanced Materials. Based in Manchester – with outposts already planned for Leeds, Sheffield, Liverpool, Imperial College London, Oxford and Cambridge universities, the National Nuclear Laboratory and Culham Science Centre – the institute starts with a budget of £235 million to build a new home "shoehorned into the campus" at the University of Manchester. It will have all the facilities and equipment needed to take materials research from laboratory to production line. "It needs to become the UK's national institute for advanced materials. That is hugely important."

With its home in the north west, the Royce, as she calls it, is seen as a part of the 'northern powerhouse'. It has to support the economy of the north west, she says, and is "a huge responsibility. We have to make sure that the Royce is a national centre, for all of the community, that can provide the capabilities for a world-class materials sector across the UK." It has to have its doors open to materials companies of all sizes as well as academics. Baroness Brown also hopes that companies will want to establish a physical presence in the new institute, and in those set up by partner organisations. She foresees a role for the institute working with the Catapults. "The Advanced Manufacturing Catapult is an obvious one."

The institute also has to play its part in accelerating research out of universities, into existing companies or new businesses, she insists. Here, the Royce will have the advantage of the National Graphene Institute on its front door. Not only does that have facilities that are still under development, it also has an incubator, which is a building for accelerating applications and building new businesses. "That is a facility that I hope we will be able to share with them."

One way of looking at the new institute could be to think of it as a nationwide version of the UTC that she set up in Cambridge with Rolls-Royce. This time it will bring together as many universities and companies as possible.

BIOGRAPHY

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

CAREER TIMELINE AND DISTINCTIONS

Born, **1954**. Awarded a first bachelor's degree in natural sciences, University of Cambridge, **1975**. Awarded a PhD in fracture mechanics, University of Cambridge, **1978**. Lecturer, University of Nottingham, **1980–1987**. First Royal Academy of Engineering Senior Research Fellow, **1987**. Senior engineering roles at Rolls-Royce, **1994–2002**. Fellow of the Royal Academy of Engineering, **1997**. Commander of the Order of the British Empire, **1999**. Chief Executive, Institute of Physics, **2002**. Principal, Engineering Faculty, Imperial College London, **2004–2006**. Vice-Chancellor, Aston University, **2006–2016**. Dame Commander of the Order of the British Empire, **2012**. Life peer, House of Lords, **2015**. Chair, Sir Henry Royce Institute for Advanced Materials, **2016–present**.

HOW I GOT HERE

Orla setting up microphones that demonstrate the acoustic frequency response for typical listeners of different heights. Each pair of microphones represents a pair of ears

Q&A

ORLA MURPHY
AUDIO ENGINEER

Orla Murphy is an audio engineer at Jaguar Land Rover. Her role focuses on optimising and improving the sound systems in the company's vehicles, combining her passions for science, maths and music.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

I always enjoyed maths and science lessons at school – and was good at both subjects – so when I was 16, I entered the BT Young Scientist competition in Ireland. I really loved the experience of scientifically investigating a problem and coming up with a solution. It really sparked my interest in science and engineering as a future career option.

HOW DID YOU GET TO WHERE YOU ARE NOW?

The main subjects I studied at school were physics, maths, chemistry and music. It was hard to find a university course that combined all of these interests, but I eventually chose a degree at the University of Glasgow that had elements of both engineering and music. It was a master's degree in electronics with music, and I really loved it! During my degree, I also did two internships: the first was at BT, where I was a research intern, completing subjective tests into the perception of video quality with different methods of encoded video (where video input has been converted into a digital format). The second internship was at Jaguar Land Rover's Global Design and Engineering Centre. At the end of this internship, I was offered a place on the graduate scheme, which I eagerly accepted as the job was well suited to both my degree and interests. I liked the fact that the graduate scheme included lots of training and development to help me adapt from studying to being a full-time engineer.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

The last year or so has been a really exciting time for me. I was named the Young Woman Engineer of the Year in December 2015 by the Institution of Engineering and Technology (IET), and then in July 2016, I was one of five winners of the RAEng Engineers Trust Young Engineer of the Year award. As a result of these awards, I have had the opportunity to reach out to many young people, through talks in schools, at science festivals and in universities. I think I've been given a great chance to be a role model for young people in STEM, and to encourage more young people to join this great profession.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

I really enjoy solving problems, and I like the fact that my job is constantly evolving with new technology. Engineers have to adapt and use cutting-edge technology, so your role is always changing and developing. I can't imagine a career doing anything else.

TELL US ABOUT SOME OF THE CUTTING-EDGE TECHNOLOGY YOU HAVE WORKED WITH

I completed a two-month international placement in Portland, USA, to work in the Jaguar Land Rover open-source technology centre. While I was there, I worked on developing a driving simulator, which is almost like a computer game that uses real-time inputs from a vehicle rig and surrounds the 'driver' with curved screens that fill their peripheral vision. We also use lots of cutting-edge technologies in-house that are developed for specific jobs.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

I start work at 7.30am, in the Electrical Test Lab where I will connect a prototype car to my laptop in order to work on improving its sound system. This involves trouble shooting, detailed acoustic measurements, and equalisation or optimisation of the frequency response. It is also important to test and validate the sound systems and features on the road to see how they perform while driving. The aim is to make the vehicle acoustics feel like the driver is in a concert hall! Once the measurements have been taken, I then start making changes in the software of the amplifier to optimise the acoustic response.

Outside of work, I am also taking a part-time Six Sigma Black Belt course, which is teaching me a set of management and problem-solving techniques that are intended to improve business processes by reducing the probability that an error or defect will occur. This means that I am learning best practice processes and techniques for tackling hard problems, which I can apply to my job in audio.

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

I would encourage them to try to get some work experience in different areas of engineering and science to see what they do and don't enjoy. If you know that you like problem solving but are not sure what type of engineering you want to study, many universities offer a common engineering first-year curriculum that you can then narrow down and focus on a specialist field in subsequent years.

Another piece of advice is to try find an engineer in the type of area you could see yourself working in, and sit down with them. Ask them about their job, what it involves and what their course was like. Having someone with experience to test your ideas with will really help you decide what is right for you.

WHAT'S NEXT FOR YOU?

I am hoping to finish my training as a Six Sigma Black Belt problem solver through work-based projects at Jaguar Land Rover. At the end of the course, and with a few additional master's modules, I will hopefully receive an MSc in Engineering Process Excellence. I am also hoping to become a Chartered Engineer with the IET. I want to continue to reach out to the next generation of engineers and to encourage them to consider engineering.

QUICK-FIRE FACTS

Age: **27**

Qualifications: **Master of Engineering, Applied Mathematics**

Biggest inspiration: **Marie Curie**

Most-used technology: **in-house audio software, Minitab Statistical Software**

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

Orla has been working on optimising the sound systems in Jaguar Land Rover cars for four years, after completing an internship in the same team while at university

INNOVATION WATCH

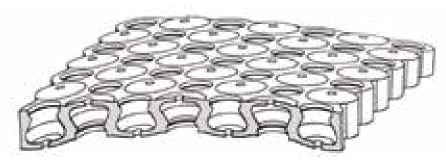
THIN AND FLEXIBLE BUT TOUGH PROTECTION

Armourgel, an energy-absorbing material that can be incorporated into clothing, is being adapted from its origins in sportswear into a protective device for the hip that aims to protect the weak and fragile hip bones of osteoporosis patients and frequent fallers.

Dr Dan Plant, then an engineering PhD student at Imperial College London, had the idea for Armourgel when he was racing motorbikes in Europe; it was far too hot for traditional motorcycling protective clothing and he needed a solution.

He began working on a new protective material by testing combinations and layers of different composites and using softer, more flexible resins, instead of the hard resins covered in multiple textile layers that protective clothing is traditionally made from. His team tested around 2,500 different compositions before finding the optimum combination that resulted in a light, thin, yet protective material, made from a synergy of a thickening polymer and an auxetic geometry.

This resulted in a material that combines the properties of a smart material with a clever internal geometry. The smart material, shear-thickening polymer, is soft and flexible, but absorbs shock and stiffens momentarily on impact. The material has a different response at different strain rates. When moved slowly it is soft and flexible, allowing it to move with the musculature of the body, but when it is subjected to impact it momentarily stiffens, absorbing energy and spreading the load.



Armourgel's internal auxetic structure, which compresses and absorbs energy upon impact

The active polymer absorbs a large amount of energy by itself. However, to create Armourgel, it is then moulded into an auxetic cellular geometry to increase the shock absorption. The three-dimensional inward-pointing shapes and open cellular structure of the auxetic geometry have thick cell walls that compress and absorb energy upon impact by collapsing in on themselves, dragging more material to the impact site and increasing performance by up to 300%.

Most energy-absorbing materials are foam based, and these can fracture upon impact. After stiffening, the cells bounce back and Armourgel returns to its original state undamaged and ready to be used again. It can also be fine-tuned to react to different types of pressure and can withstand temperatures ranging from -20° to 50°C.

The technology was first used in clothing for extreme sportswear. Dr Plant applied for and was awarded a Royal Academy of Engineering Enterprise Fellowship, which provided him with funding and mentoring from an engineering leader to help him develop and commercialise Armourgel for the medical market. The first development he focused on was a preventative measure for hip fractures after learning that these injuries account for 15% of orthopaedic hospital beds, costing the NHS £2.4 billion a year.

In order to use the technology to create a preventative device for hip fractures, the team needed to design something that could provide the necessary protection, but was also comfortable enough to be worn on a daily basis under regular clothing. As Armourgel has high energy-absorption levels, it can be used in a much thinner layer and integrated within garments.

As a lighter and thinner material, Armourgel can be used on lightweight sports clothing

As the company continues to expand into new markets and applications, the technology will be used in helmets for use in areas such as the military, racing and sports. Dr Plant hopes to produce Armourgel products to sell directly to consumers and set up an advanced manufacturing centre in the UK.

For more information, visit **www.armourgel.co.uk**

HOW DOES THAT WORK?

POWERLINE NETWORKING

Most homes and businesses use a wireless network so powerline networking, which uses electrical wiring as a data network, is often considered to be an outdated and redundant technology. However, it's a simple technology that complements wireless by reaching those areas that might be beyond a Wi-Fi network

Powerline networking, or powerline communications, is a form of communication that uses electrical wiring to carry both data and alternating current (AC) electrical supply through existing electrical infrastructure. Powerline networking can have a range of uses. In the home it is mostly used for home automation (smart home) and internet access, but it is also used in industrial and commercial settings, for example by utility companies to carry out tasks such as remote meter readings.

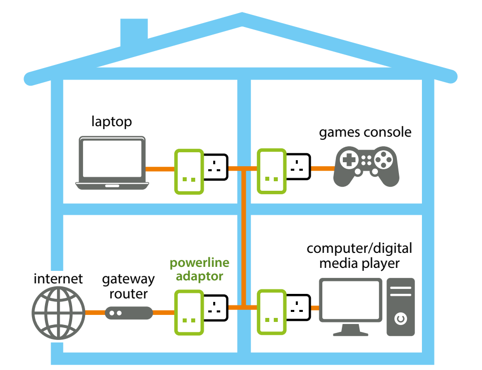
The powerline is able to carry data via the superposition of a low-energy information signal to the power wave, which means they can pass through each other without being disturbed. Data is transmitted at a minimum of 3 kHz to ensure that the power wave does not interfere with the data signal. Electrical wiring in the home is able to transmit signals at a variety of frequencies. Electricity usually travels at 50/60 Hz frequencies, meaning that data can use the same wires, but at a much higher frequency so that the two do not affect each other.

To install powerline networking in a home, two special adaptors are needed. The first powerline adapter would be connected to an existing wired local area network router, and the second adapter would be attached to an Ethernet-ready device such as a computer or television. When both adapters are plugged in, a network connection will be established internally through the electrical wiring between the two wall sockets, meaning that other than the power cable, no extra wires are needed to connect the device to the router. It can be used for wireless printing, playing music to remote speakers, file sharing in homes with multiple computers, connecting televisions to the internet, and gaming.

In home automation systems, powerline communications can be used for controlling lights, heating, air conditioning, cameras, and security systems. The concept of a smart home has been around since the 1970s, when a Scottish company invented X10, a system that allowed compatible home devices to communicate via the existing wiring. A transmitter, such as a keypad or remote control, could send a message in numerical code over the existing wiring to a receiver, for example to turn off a lamp (the receiver) in another room. The message sent over the wiring would include which device the message was being sent to and the command for the device. X10 devices can receive a range of commands, such as turn all devices off, turn all lights on, or dim lights. The system is still in used in many homes, but some smart-home systems now use radio-waves to send signals instead, making use of Bluetooth and Wi-Fi networks.

In industrial and commercial settings, powerline networking has various uses. It has been used in the smart grid for advanced energy management, fraud detection, automatic meter readings, street lighting control, and remote metering and billing.

A powerline networking connection has some advantages over a wireless connection, but how well it works will still depend on the quality of the domestic electrical system. Inadequate wiring and circuit breakers in between the connected cables can negatively affect performance and cause interruptions. It can also be affected by other motorised home appliances, such as vacuum cleaners or fans, which generate noise in the power grid and, as the wiring and associated switchwork is optimised for AC power, the connectivity does not work as well. However, the system can make it easier to extend a network to distant areas of a house that regular Wi-Fi might struggle to reach. It can be a low-cost way to increase the connectivity of the home, as all homes already have multiple AC outlets, and the only extra equipment that is needed is two adaptors per device to be connected.



Multiple devices can be connected to the internet via their power leads

Not all fast computers reach Mach 2

Eurofighter Typhoon

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