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The upper bow of the HMS Queen Elizabeth aircraft carrier is lifted into place
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This QR code links to www.ingenia.org.uk containing a searchable archive of all Ingenia articles

EDITORIAL

WHAT'S IN STORE FOR ENERGY

Dr Scott Steedman

After years of anticipation, batteries that can store enough energy to power a house are on the market in the UK. The concept is simple: domestic systems can reduce homeowners' energy costs by storing energy when there is excess supply and releasing it when grid demand and electricity prices are high. The batteries are charged through domestic solar arrays or some other microgeneration system; smart control systems can take the house off-grid temporarily or moderate its electricity demand to suit grid conditions.

Driven by the development of electric vehicles, battery technology has progressed rapidly in recent years. The new 'behind the meter' batteries sit inside the house, with software systems controlling their charge and discharge cycles. Industry interest is growing rapidly. Last year, Tesla Motors announced a 'Powerwall' battery for domestic use, with the first UK installation in February this year. A British start-up, Powervault, launched its products in April with units that resemble a dishwasher.

Global players are also taking an increasing interest in electricity storage. Working with three British universities, E.ON is testing a 2 MW battery unit at Western Power Distribution's Willenhall substation, near Wolverhampton. In May, energy company Total announced the acquisition of Saft, the French company specialising in industrial battery technology. In the same month, car maker Nissan announced plans to pilot its vehicle-to-grid technology in the UK, which will see car owners able to offer stored energy back to the grid.

Managing the peak demand for electricity has long been recognised as an essential element of the future energy mix in the UK. The challenge is moving from a centralised system to a dynamic smart-grid approach and 'demand side response', where businesses and consumers can manage their own demand and supply interactively.

Distributed energy storage could not only unlock benefits for the individual consumer but for the entire supply chain. With the right technology, market structures and regulatory framework, supply, generation and distribution companies also stand to benefit. Energy retailers will avoid peak charges by smoothing out demand. Most important of all, with a large enough network of commercial and domestic energy storage, operators will be able to draw on stored energy to cope with unexpected surges. Aggregated together, the nation benefits through the improved efficiency of the whole system.

In the corporate energy market, the focus is on innovative services to manage demand and link storage to the grid. Start-ups such as Open Energi offer their clients technology that enables them to reduce consumption minute by minute, releasing power to be used elsewhere, like a virtual power station.

Green Energy Options, based in Cambridge, is a start-up that develops home energy monitoring and control systems and is pressing for similar innovation in the residential market. The company published a discussion paper on residential battery storage in April that argues that from the consumer perspective alone the business case is weak. The real opportunity lies in finding innovative ways by which batteries can interact with the grid and share benefits.

Regulations will have to change as well. With more than 140,000 new homes being completed each year in England alone, the new house market should be an easy target for the promotion of energy storage. Building regulations in England and Wales, and in Scotland, have been tightened up to require new houses to incorporate microgeneration and high levels of insulation, but the regulations offer no credit for energy storage as an alternative to microgeneration.

On the engineering side, building trust will require simple interfaces that make it obvious what's going on and allow consumers to override the system. Batteries need to be integrated with other electrical technology in the home, such as heating, domestic appliances and microgeneration systems. In addition, new control systems are needed that optimise battery use in terms of charge and discharge cycles over the battery's lifetime.

Widespread roll-out of commercial and domestic energy storage could bring substantial benefits to industry and consumers. The transition to a dynamic grid is just the first step. Rapid development of the market requires an approach incorporating regulation, technology and the supply chain, aimed at building trust and changing behaviour among businesses and consumers if they are to fully embrace these new products and services.

Dr Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

INGENIOUS AWARDS

A young girl learns at one of the many public engagement engineering projects supported by Ingenious © Engebretsen

Through its public engagement grant scheme, *Ingenious*, the Royal Academy of Engineering has this year funded 23 new projects that will allow engineers to engage the public in innovative ways.

The scheme supports projects across the UK to run activities that give engineers the opportunity to share their stories, expertise and passion for technology with audiences ranging from school groups to retired people. A major aim of the scheme is to encourage engineers to develop their communications and engagement skills.

Projects that have been funded this year include Heart in your hands, an interactive experience where people can get 'hands-on' with robotic hearts that mimic the structure and function of normal and diseased human hearts. Visitors to events in Birmingham, Bristol and London will be able to discover the engineering behind the heart, and how it works and adapts to disease.

A Stemettes Hackathon weekend for young women at Imperial College London has also been funded. The Stemettes are a group of women working to inspire and encourage girls and young women into STEM careers. The Hackathon will see 50 female school students aged 12 to 18 learn programming techniques and develop their own app, game or website. The students' finished products will be presented to a panel of expert judges, and participants will have the opportunity to ask professional engineers and computer scientists about their careers.

Other projects funded this year include an engineering-themed photography competition in London and a project from Techniquest Glyndwr that will encourage over 4,000 members of the local community to go on an engineering adventure in North Wales.

Ingenious is supported by the Department for Business, Innovation and Skills and has funded more than 140 projects to date, providing opportunities for over 2,000 engineers to take part. A full list of projects funded by the scheme can be found at **http://bit.ly/1WeZmwf**

FIRST UK ROBOTICS WEEK

The first UK Robotics Week will take place between 25 June and 1 July 2016 to showcase leading UK technology and research in robotics and autonomous design, as well as engage and inspire school, college and university students.

The week-long series of events and activities will be built around a nationwide competition called the School Robot Challenge, which will invite pupils across the UK to submit robotics-inspired essays or artwork, or design their own robotic bug. The competition hopes to engage children aged 4 to 17 years old with STEM subjects and encourage them to develop new skills.

During Robotic Week, the finals of a number of international academic challenges will take place.. Robotic research groups from around the world will come to the UK to demonstrate their latest technologies in surgical robotics, field robotics, autonomous driving and unmanned aerial vehicles.

UK Robotics Week is being coordinated by the Engineering and Physical Sciences Research Council's UK Robotics and Autonomous Systems (UK-RAS) Network, and is supported by the Royal Academy of Engineering, the Institution of Engineering and Technology and the Institution of Mechanical Engineers.

UK Robotics Week is showcasing leading technology and research looking at areas such as how robots can learn from and cooperate with humans as they become more capable © UK Robotics Week/EPSRC UK-RAS Network

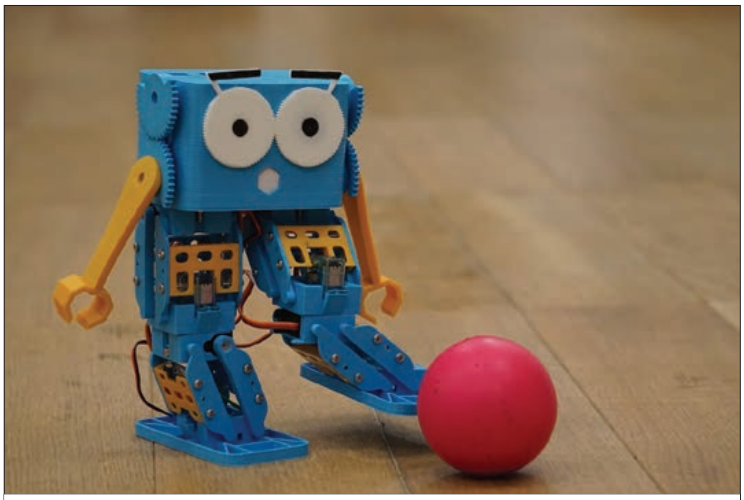
The full programme includes open robotics labs, public lectures and industry showcases, among many other events. Further details can be found at **www.roboticsweek.uk**

ENTERPRISE FELLOWSHIPS AWARDED

The Royal Academy of Engineering's Enterprise Hub has awarded eight UK researchers Enterprise Fellowships to help them start up companies based on their innovations.

The Fellowships provide funding of up to £60,000 and aim to help researchers get new technologies to market. The Hub provides its members with a full package of bespoke support, covering everything from building a business plan to pitching to investors. It also offers mentoring from Academy Fellows, including leading engineering entrepreneurs including Sir Robin Saxby FREng, former Chief Executive of ARM, and Professor Neville Jackson FREng, CTO of Ricardo. The eight awardees include Dr Damian Coyle from Ulster University, whose start-up NeuroCONCISE is developing a headset that reads brain activity and allows people to communicate without moving. The technology has huge implications for those left without the ability to move following a stroke, or brain or spinal injury. By imagining the movement of an arm or leg, people who are physically impaired will be able to communicate with doctors and loved ones.

Another researcher, Dr Alexander Enoch of Robotical Ltd, has developed a 3D-printed programmable robot that can be used as an educational resource to help people learn to code. The robots have already been successfully used to teach children.



Dr Alex Enoch's 3D-printed robot can be programmed to walk, dance or even play football, and can be controlled by a smartphone © Robotical Ltd

Other technologies funded include a fibre-optic probe that screens for cancer, and bricks made of 90% recycled materials that could reduce greenhouse gas emissions and waste across the construction industry.

Follow the Enterprise Hub on **Twitter @RAEng_Hub**

CELEBRATING WOMEN ENGINEERS

School pupils take part in an experiment at Winchester Science Centre during NWED 2015 © NWED

The achievements of women in engineering are being highlighted in a range of events across the UK, with an aim to inspire the next generation.

The Women's Engineering Society (WES) is marking National Women in Engineering Day (NWED) on 23 June. The day aims to raise the profile and celebrate the achievements of women in engineering, and encourage girls and women to pursue careers in the field. Employers, schools and colleges, women engineers and professional engineering institutions are being encouraged to hold events, such as organising women's networking events, opening up engineering workplaces for student careers visits or asking women engineers to give talks in schools. The sub-theme of the day is 'raising profiles' and a list of the 50 most influential women engineers, nominated by peers and backed by WES, will be published in the *Daily Telegraph* on 23 June.

One of the goals for this year is to sign up as many girls as possible to WES's SPARXX network (www.sparxx.org.uk). The network provides news and information, such as events and career opportunities, for girls interested in technology, engineering, science and art, with the aim of inspiring and helping them on the path they choose to take.

In 2015, more than 500 events were held across the UK on the day and around 350 schools took part. Events included a gathering of over 800 people working in transport, engineering and technology at Horse Guards Parade, who broke the Guinness World Record for the most people performing a jumping high-five simultaneously, and an NWED event in Scotland attended by HRH Prince Charles that was organised by Selex ES. The official #nwed2015 hashtag trended on Twitter for more than nine hours and the day attracted significant media coverage, both nationally and internationally.

To mark International Women's Day on 8 March, a page was launched on the Royal Academy of Engineering's website celebrating the women engineers in the Fellowship. In the 43 profiles on the page, the women Fellows discussed their greatest engineering achievements, and what they would say to someone considering a career as an engineer. The profiles included: Dr Dame Sue Ion DBE FREng, Chair of the Nuclear Innovation Research Advisory Board; Professor Carole Goble CBE FREng, Professor of Computer Science at the University of Manchester; Dame Judith Hackitt DBE FREng, Chair of the EEF; Professor Claire Adjiman FREng, Professor of Chemical Engineering at Imperial College London; and Dr Liane Margaret Smith FREng, Managing Director of Wood Group Intetech Ltd.

More information about NWED and resource packs can be found at www.nwed.org.uk. To view the profiles of the Academy's Fellows, please visit **www.raeng.org.uk/IWD2016**

GEARED UP FOR OLYMPIC SUCCESS

A team of engineers at BAE Systems has developed an advanced cycling ergometer with the British Cycling team to help them prepare for the Rio 2016 Olympic and Paralympic Games this summer.

The ergometer measures the work rate and energy expended by cyclists and is capable of accurately replicating the centrifugal forces of a velodrome.

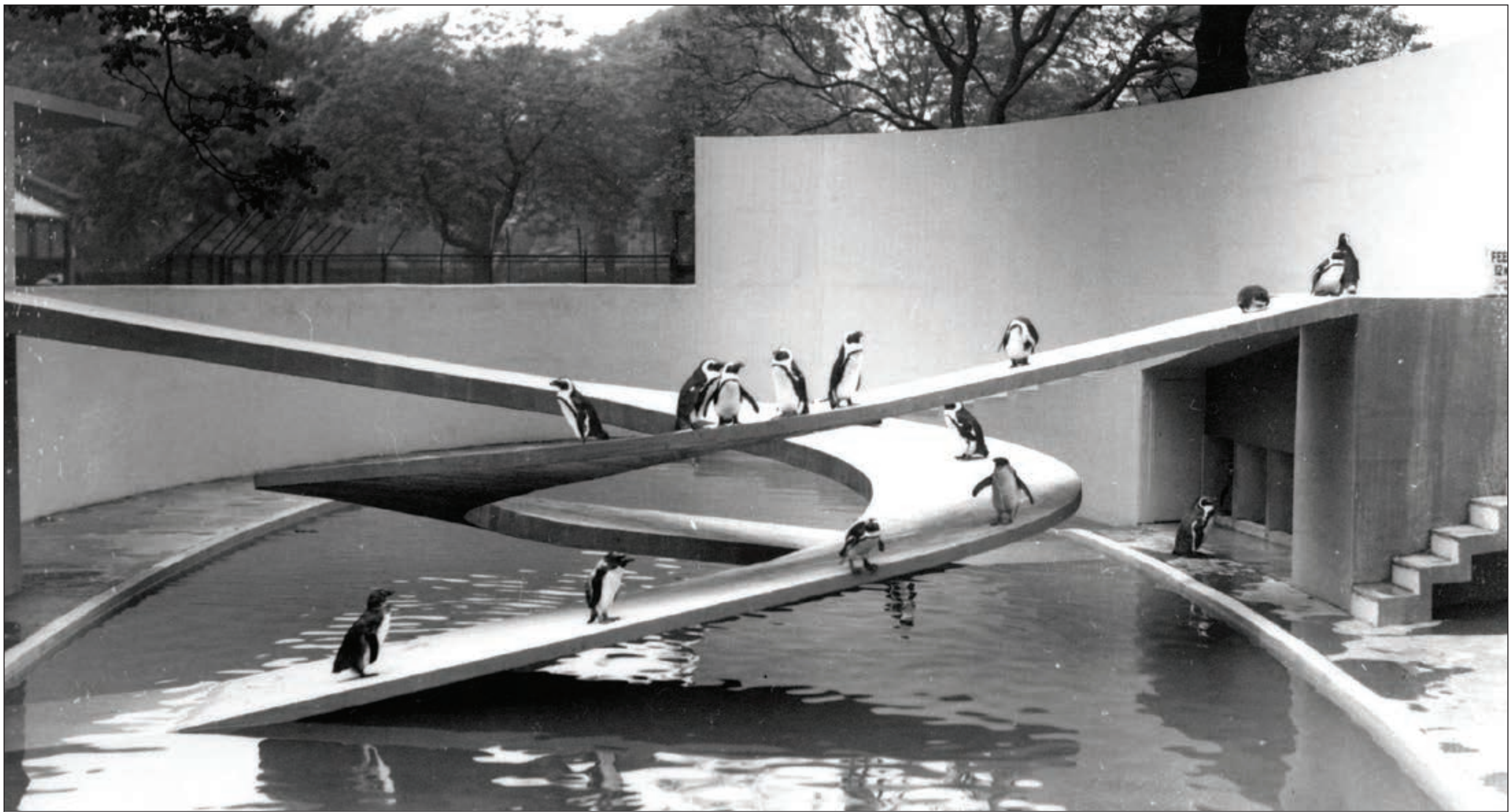
While similar in appearance to a normal static exercise bike, its technology consists of a large variable fly wheel at the rear that has adjustable blades to increase or decrease resistance on the pedals. It can also simulate different gear ratios and generate force for the cyclist based on their individual load and the track they are riding on.

The ergometer was created upon request for the British Cycling team, who asked for an adaptable training system that could be customised for different riders and events. In addition, the design allows it to be used for data collection in laboratory conditions, collecting gas and blood for analysis and testing at high speeds to examine athletes' technique.

BAE Systems' Technology Partnership with UK Sport began in 2008 and has developed engineering solutions for more than 30 different sports, including taekwondo, athletics and wheelchair basketball, benefiting over 200 Olympic and Paralympic athletes.

Find out more about the Technology Partnership at **http://bit.ly/1Q2Qwu6**

A member of the British Cycling team tests out the advanced cycling ergometer © BAE Systems



The iconic Penguin Pool at London Zoo, designed by Ove Arup in 1934 © ZSL/Victoria and Albert Museum London

ENGINEERING SEASON AT THE V&A

The Victoria and Albert Museum (V&A) presents its first engineering season this summer, featuring a major retrospective of celebrated engineer Ove Arup and a nature-inspired installation, constructed by robots.

Engineering the world: Ove Arup and the philosophy of total design will run between 18 June and 6 November 2016. The exhibition will span 100 years of engineering and architectural design, looking at Ove Arup's work and legacy – from his writing about design and his early projects, such as the Penguin Pool at London Zoo and the Sydney Opera House, to the Arup firm's more recent work, including the Leadenhall building and the Crossrail project. Previously unseen prototypes, models, archive material, drawings, film and photography will be on display, as well as immersive digital exhibits using animation, simulations and virtual reality.

The exhibition is complemented by a temporary installation in the museum's garden. The *Elytra Filament Pavilion* consists of a rolling canopy of tightly woven carbon fibre cells, inspired by the structure of the forewing shells of flying elytra beetles, created using an innovative robotic production process. The pavilion will grow over the course of the engineering season in response to data on structural behaviour and patterns of activity in the garden, which will be captured by sensors in the canopy. New cells will then be created by an onsite robot, developed by industrial robotics firm Kuka. The installation, created by experimental architect Achim Menges, structural engineer Jan Knippers, climate engineer Thomas Auer and Moritz Dörstelmann, a research associate at the Institute for Computational Design, University of Stuttgart, is in place from 18 May until 6 November 2016.

A free display in the V&A + RIBA Architecture Gallery, *Mind over Matter,* will showcase major engineering projects by British firms including AKT II, Atelier One, Buro Happold, Expedition Engineering and Jane Wernick Associates. Other activities across the season include: an Exhibition Road engineering residency supported by the Heritage Lottery Fund, a themed Friday Late, a series of lectures and gallery tours, and a symposium about biomimicry, design and engineering with a keynote lecture by Achim Menges.

Visit the website at **http://bit.ly/1OTVIjA**

The Elytra Filament Pavilion in the V&A John Madejski Garden 2016 will be continuously constructed by robots © ICD/ITKE University of Stuttgart/Victoria and Albert Museum London

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

LETTERS

GENDER PARITY IN ENGINEERING

Earlier this year, I was pleased to be invited to take part in the Royal Academy of Engineering's *Celebrating leading women in engineering* initiative. A dedicated page on the Academy's website highlights the women engineers in its Fellowship, with the aim of encouraging more people, particularly girls and women, to consider and persist in engineering careers.

Analysis by Engineering UK highlights that we will need more than 180,000 new engineers and technicians each year to 2022 to fulfil demand. However, research from the Institution of Engineering and Technology (IET) shows that just 9% of engineers in the UK are women – the lowest percentage in Europe, and a figure that has remained static for decades.

There are so many big and small, global and local challenges that engineers need to crack, with not enough engineers available to do so. There are surveys from organisations such as McKinsey & Company, *Harvard Business Review* and the World Economic Forum that conclude companies and countries with better gender parity have higher earnings before interest and tax per capita. Therefore, attracting more women into engineering is a compelling economic, as well as social, issue.

So why do so few women see engineering as a career for them? I think it is the result of a number of factors: from the careers advice offered at schools, to schools not giving girls the confidence to opt for science and maths A levels.

It is also due to some employers needing to make their approach to recruitment and retention more inclusive. There are skilled women qualified to take up existing roles, but many are leaving the profession as soon as they graduate because the opportunities advertised do not look like ones where women can thrive.

I firmly believe that if more companies published their diversity figures, there would be greater clarity about what kinds of measures are working in attracting more women to the industry. This is one of the recommendations made in the IET's joint report with the Prospect trade union, *Progressing Women in STEM Roles*.

Finally, there is a wider image problem for engineering in the UK. Before I became the IET's first female president in its 145-year history, I was president of Sony Media Cloud Services, based in California. There, I noticed that engineers are understood to be doing things which are making a difference in the world and they have an almost 'rock star' status as a result.

To attract a new generation of engineers who can really deliver on the UK's engineering and technology potential, we must showcase engineering as a career that is creative, diverse and makes a difference in the world.

We need more role models at every level to inspire young women by showing them what engineering and technology could look like for them. The whole of the engineering profession, including men, must pull together to help win this battle. There is no quick or simple fix; instead, we need many small and subtle changes over time.

I can honestly say that working as an engineer is one of the most exciting, fast-moving and challenging places to be at the moment. I want to motivate other women to share my passion and come and join me.

Naomi Climer FREng
President, Institution of Engineering and Technology (IET)

THE INNOVATION NEEDED IN MATHS EDUCATION

In his March editorial *Convincing the social artists* (*Ingenia* 66), Dr Scott Steedman suggested that in order to plug the engineering skills gap, school maths teaching should be transformed by drawing on the online digital technology that children already use. The reasons for this suggestion are many.

The OECD 2015 Programme for International Student Assessment (PISA) says Britain has fallen to 26th in its numeracy and literacy rankings; 20% of our 15 year olds are low mathematical performers and only 12% excel, compared with 4% and 55%, respectively, in Shanghai. Possible consequences of the worrying national maths deficit include long-term unemployment and critical skill shortages, notably affecting engineering.

There are reasons to believe that the heart of the problem is underachievement in basic numeracy and logical mathematics in children under 12. Without a suitably well-founded and inspiring educational experience between the ages of seven and 11, far too many 14 to 16 year olds find that they are irreversibly excluded from STEM careers. The situation is not helped by a shortage of maths teachers and the recent 11% short fall in applications for maths teacher training. The government is funding training of numerically minded graduates from other disciplines, but this alone is unlikely to plug the gap.

Tellingly, *The Economist* recently noted that much teaching has hardly changed since the Middle Ages, yet children increasingly use computers for research, essay writing and social purposes. Meanwhile, the *Guardian*'s Tim Gowers asked whether mathematics education could better accommodate the needs of the majority of children, perfectly aware they will never reach sunny STEM uplands but nevertheless need to be able to tackle life problems, see through incorrect arguments and make better decisions.

Dr Steedman's editorial suggested that higher education's MOOCs (massive open online courses) could act as a pathfinder. Assisted, blended online learning approaches can leave teachers in control, happy regarding their primary role and free for more individual intervention. Unsurprisingly, this seems to be the way maths e-education is going, according to a number of examples I have recently come across. *MyMaths'* personalised student attention, feedback and administration seems especially helpful to teachers for whom maths is not their primary subject. *Hegartymaths.com*'s apps that augment GCSE and A-level maths have been viewed more than 5.5 million times across the world. Teachers grasp and adopt the online game *Minecraft* quickly, using it to teach subjects such as maths and engineering in more than 10,000 establishments around the world. *Cornerstone Maths* focuses on cognitive aspects, while *Trymaths* offers tracking and marking help and *Grid Algebra* successfully engages pupils who have previously failed. Oxford University Press, Pearson, Kaplan and Apollo also offer enhanced online versions of their textbooks. While cumulatively this is an appetising à la carte menu, some may be put off by the negative correlation between PISA's findings on mathematic achievement and students' technology access. However, a recent OECD *Teaching and Learning International Survey* partly attributes this to not understanding how these resources can be used, with clear evidence that emphasis on cognition improves attainment and motivation.

So what might be done to remedy our rather unhappy national position? Should the proposals in the Joint Mathematical Council of the United Kingdom's 2011 report, *Digital Technologies and Mathematics Education*, be realised in the form of a *Which*-style cost-benefit study of what scalable technology can and can't do for students, parents and teachers? Since teacher training is essential, should the recent Advisory Committee on Mathematics Education *Beginning teaching: Best in class?* recommendations be expanded to cover using digital technology and social media? As tablets become ever more affordable and many seven to 11 year olds own one, is there a national case for making them the platform for resilient e-learning? How about building on virtually every nine year old's keenness to learn and astonishing comfort with digital technology and social media tools? Come on, maths movers and shakers, engineering needs your help!

Dr Ian Nussey OBE FREng
Recently retired from IBM

OPINION:

ROBOTICS AND AUTONOMOUS SYSTEMS – AFFECTING EVERYTHING THAT MOVES

A revolution in smart machines will affect all sectors of the UK economy and our personal lives. Professor David Lane CBE FREng, Founding Director of the Edinburgh Centre for Robotics and lead author of the *RAS2020: Robotics and Autonomous Systems* strategy, argues that the UK has made a promising start in leading technology and skills development, public understanding and the development of ethical frameworks, but there is more to do.


Professor David Lane CBE FREng

At the State Opening of Parliament on 18 May 2016, the Queen's Speech contained the memorable phrase: '*My ministers will ensure the United Kingdom is at the forefront of technology for new forms of transport, including autonomous and electric vehicles*.' Such a statement demonstrates how the government has recognised the importance of this robotic technology to the future of our economy and society, and has made a commitment to put the UK at the forefront internationally.

There's a revolution happening around us and all over the world. Smart, connected machines or robots, making independent decisions and even learning, are emerging from research tools into practical applications ('Autonomous systems', *Ingenia* 65). Autonomous and semi-autonomous cars on our streets are only one example. Other robotics and autonomous systems (RAS) include manufacturing systems that can personalise designs and reconfigure on the fly; robotic fulfillment centres that assemble, package and dispatch goods ordered online; drones that deliver packages, or map, inspect and repair offshore oilfields and nuclear facilities; assistive exoskeletons to help us move and lift; and interactive companions for the elderly and isolated. In the same way that the information and communications (ICT) revolution affected everything that uses data, the RAS revolution is changing everything that moves.

It's happening now, and globally, for two reasons. First, silicon has been mastered to the point where a chip can hold enough processing power to run computationally intensive tasks at real-world rates. Second is productivity. Nations all over the world have recognised that these smart machines can make people more productive, and give economies and organisations a competitive edge. A global race has therefore emerged to determine who will lead on the development and application of these technologies, to reap the economic benefits, to ensure security and to lead in responsible innovation.

The heart of this revolution is the software that 'makes dumb-iron smart'. As

As number two in the world for programmers… the UK is well placed to be an innovation leader in smart machines

number two in the world for programmers, coupled with strong traditions of algorithmic expertise from its world-class science base, the UK is well placed to be an innovation leader in smart machines.

For these reasons, in 2013, Lord Willetts, then Minister for Universities and Science, included RAS as one of 'eight great technologies' with potential to support jobs and growth, and commissioned a Special Interest Group to review the UK landscape and develop a strategy. Published in the summer of 2014, the strategy proposed competitions to build and demonstrate useful RAS, running in environments where it can be made safer and where the public can be engaged in their use. The strategy also highlighted the need for the government to create the best international regulatory environment and standards, alongside measures to coordinate government and industry activities, promote innovation clusters and invest in skills development at all levels.

To date, the strategy has guided over £200 million of government investment in research, training and innovation, including four research centres for doctoral training, capital equipment, and the Centre for Connected and Autonomous Vehicles, which is run jointly by the Department for Transport and Department for Business, Innovation and Skills. RAS innovation clusters (regional groups that work together on initiatives and projects) are now emerging in Bristol, London, Oxford, Southampton, the North West and Edinburgh.

However, the adoption of RAS brings change. Labour markets will adapt as RAS work alongside us, reducing human involvement in dull, dirty and dangerous tasks. There could be short-term layoffs and redundancies; however, historical precedent of similar technological evolutions (such as looms, motorcars, ICT) shows the net effect on employment will be positive in nations that embrace these changes. The creation of new jobs and the inevitable lay-offs point to the need for training in schools, apprenticeships and universities, for access to mid-life re-training, and support for innovation schemes.

Building public consensus and support is essential in establishing trust for any adoption. The public currently perceives possible threats to employment, and loss of privacy and control through adoption of RAS. Ethical and legal frameworks are also required where RAS and artificial intelligence (AI) systems are making decisions with consequences for people. Efforts to develop these frameworks are starting, and critically involve engineers, social scientists, lawyers, ethicists and journalists working together. The public narrative to date has not involved all of these stakeholders properly, driven more by Hollywood fiction than engineering reality, and some correction is needed. The demonstrations of autonomous cars, or pods, using prepared public spaces in Milton Keynes and Greenwich this summer will be instrumental in developing this narrative.

Although the UK has made a promising start, other nations are not standing still. The USA, Germany, South Korea, Japan and now China have active programmes to develop RAS. The UK cannot afford to be complacent, and must maintain its momentum to be globally competitive. Examples of next steps include further development of test-beds (or living labs) for de-risking (proving the product works, thereby reducing commercial risk and increasing customer trust) and social experiment in sectors beyond transport; mapping of value chains to understand disruptions and where opportunity lies; and linking to established work on cyber security to prevent unsafe operation through hacking.

To make this a reality, government and industry must continue to work together, creating new business from the UK's world-class RAS research and training base and defining new requirements, further refining regulations and standards for use, to make the UK the go-to place for international investment. This could be achieved through a leadership body or dedicated organisation that can coordinate relevant research activities to drive RAS innovation and target both public and private support. Start-ups will need to build relationships with, and work alongside, larger companies and government to support good business models and work towards useful end products that can be marketed.

McKinsey has estimated that RAS will have an economic impact of between $1.6 and $6.4 trillion by 2025. By fully embracing robotics now, the UK can lay claim to its share and compete globally. Standing still would simply hand the market to others.

BIOGRAPHY

Professor David Lane CBE FREng is Founding Director of the Edinburgh Centre for Robotics, a £35 million joint venture between Heriot-Watt and Edinburgh universities. He is a former CEO and Founder of SeeByte Ltd/Inc, a multimillion dollar UK/US company in defence and offshore markets. In 2013/4, he led development of the UK's national robotics innovation strategy, which has influenced over £200 million of government spend to date, and was a Director of euRobotics AISBL.

FRANCIS CRICK INSTITUTE, LONDON

The Francis Crick Institute, due to open in central London later this year, will be a world-leading centre for biomedical research and innovation. Engineer and freelance writer Hugh Ferguson talked to Steve Berry, Associate Director at Arup, and Rob Partridge, Director at structural engineering firm AKT II, to find out how the unique challenges of designing and constructing this large and unusual building were overcome.

The Francis Crick Institute, with neighbours St Pancras International station (bottom left), the British Library (top left), and housing on the other two sides. Along the spine of the building can be seen the array of 32 stacks, which discharge the equivalent of an Olympic swimming pool-full of air every 10 seconds © Laing O'Rourke

Named after the molecular biologist who, together with his colleague James Watson, identified the structure of DNA in 1953, the Francis Crick Institute is one of the largest biomedical research facilities (BRF) in Europe. It represents a particular partnership between its six founders, each of which has a long and distinguished association with biomedical research: the Medical Research Council; Cancer Research UK; the Wellcome Trust; University College London; Imperial College London and King's College London.

The institute's vision is "to discover the biology underlying human health, improving the treatment, diagnosis and prevention of human disease", and its work will address seven fundamental questions such as how a living organism acquires form and function, and how the immune system knows whether, when and how to react.

The new laboratories will draw together the founding partners' existing research activities, hence the choice of location close to their 'centre of gravity' and leading London hospitals, in the middle of a well-established research community with excellent transport connections

The new laboratories will draw together the founding partners' existing research activities, hence the choice of location close to leading London hospitals and institutions, in the middle of a well-established research community with excellent transport connections. The founding organisations wanted not only the highest-quality state-of-the-art facilities and equipment, but also a layout that encourages collaboration and cross-fertilisation between researchers across a broad range of disciplines including biology, chemistry, physics, engineering, computing and mathematics, and discourages isolated 'ivory tower' projects. They were also keen to encourage turnover of researchers and projects, providing a continuous injection of fresh energy and ideas, and to provide a facility that would be adaptable to new emerging scientific opportunities.

The main entrance to the Francis Crick Institute, viewed from St Pancras International Station, with its glass, steel and terra cotta façade and its distinctive curving steel roof © HOKGlowfrog

ENGINEERING RESEARCH

Considerable modelling and analysis was carried out on the building before construction began, including:

- Acoustics and vibration – background acoustics and vibration levels were measured and then used as the baseline for compliance and mitigation measures.
- Electromagnetic compatibility/interference – the profile of the site was assessed in order to establish background levels, as much of the research equipment is sensitive to electromagnetic emissions.
- Environmental studies – a number of studies were performed, including the impact the building would have on existing air quality.
- Daylighting – studies were performed to identify the impact that the building would have on its surroundings. This focused mainly on the housing around two sides of the site, looking at its rights of light and the amount of natural daylight entering the buildings.
- Thermal performance – the building was modelled with specialist software to confirm compliance with building regulations and to support the sustainability assessment.
- Dispersion modelling – numerical analysis to confirm that the 32 large extract air stacks and thermal flues would be compliant with emissions requirements, and wind tunnel tests to confirm that emissions would not re-enter the fresh air intakes.
- Odour modelling – conducted using both numerical and empirical testing of biomedical research facility (BRF) waste materials on exhaust streams. Mitigation mainly by filtration and dilution.

For the last four years, the institute's new building has been taking shape behind the British Library and alongside St Pancras International station, and later this year the first of some 1,500 scientists and support staff move in

The basement being excavated down to 8 m depth, 'in the open' to facilitate removal of old Victorian brick and concrete, and with a deep, thick cantilevered concrete retaining wall to protect the sensitive old infrastructure round the sides. At the bottom, a concrete slab was cast and some 260 piles were sunk. Then, construction started on the building above, while simultaneously the remaining two levels of basement were excavated and concreted beneath © AKT II

The building's design team worked closely with the scientists to turn their ideas into reality, which included challenging some of the initial design requirements. For example: some of the impossibly high rates of air change requested for laboratories were reduced to manageable but perfectly adequate rates; and high vibration resistance, required for laboratories containing sensitive equipment, was extended to all laboratories at the suggestion of the design team in order to provide greater adaptability for future use.

For the last four years, the institute's new building has been taking shape behind the British Library and alongside St Pancras International station, and later this year, the first of some 1,500 scientists and support staff move in. It is by any measure a huge building, with 83,000 m^2 of space spread over 12 storeys, four of them below ground in one of London's largest basements. But what makes it so unusual is the combination of engineering measures required to meet the exacting requirements of state-of-the-art biomedical research in a city centre building. Unprecedented levels of mechanical and electrical services have been provided to maintain the required environments within the laboratories, and in particular to safely contain the hazardous materials and bacteria involved with such research. Extraordinary measures have been taken to reduce vibration and magnetic permeability of the building to avoid affecting sensitive equipment.

CONSTRUCTION PLAN

Inside the front entrance, the largely open-plan laboratories lead out onto wide full-height atria that separate the four laboratory blocks, creating a calm and spacious environment. Behind are some of the high-containment laboratories that require a controlled environment. Beneath in the basement are the biological research facilities (BRF), more high-containment laboratories and all of the most sensitive research equipment.

The large size of the basement – covering an area of approximately 150 m x 70 m and making up almost a third of the building's size – was governed by the space requirements and limitations on the height of the building due mainly to the need to retain rights of light for the housing on two sides. As so often happens in London, digging down meant negotiating existing infrastructure. This included: two 120-year-old low-pressure cast-iron gas mains to the north; old brick-arch sewers to the north and west; the British Library's buried pumping station to the south; and the buried structure of St Pancras Thameslink station to the east, which also provides support for the new roof of St Pancras International station. The site itself was a former railway goods depot built in the 1880s, and was underlain by a dense grid of brick footings on mass concrete, to a depth of 8 m in places.

The traditional and most straightforward way to construct the building would have been to use 'bottom up' construction: complete the full excavation within propped retaining walls, sink piles as foundations, and then build the structure up from the bottom. A much quicker (but more expensive and riskier) way would have been 'top down': sinking plunge piles from ground level, casting the ground-floor slab, and then simultaneously building upwards, supported by the piles, and downwards between the piles to create the basement. This technique was used for


'Top-down' construction for the lower two basement levels, with heavy steel plunge columns supporting the building above while the basement is excavated and concreted beneath. Close to the magnetically-sensitive NMR spectrometers, the steel columns were replaced with precast concrete plunge columns incorporating austenitic stainless steel reinforcement, which reduced magnetic permeability by a factor of around 100 © AKT II

construction of The Shard ('Building the Shard', *Ingenia* 52).

After several design iterations, a compromise was chosen: conventional excavation down to the second basement level, which allowed the old masonry and concrete footings to be removed, and then 'top down' from there. This solution depended on being able to support the excavation down to 8 m depth in the temporary condition, with only minimal lateral movement of the surrounding ground; even small differential movement could have caused the sensitive St Pancras escalators to jam, or allowed the cast-iron gas main to crack and cut off gas supplies to Camden. The answer was a 1 m-thick heavily reinforced concrete diaphragm wall around the perimeter of the excavation, sunk to a depth of up to 28 m and acting as a free cantilever to support the excavation over the top 8 m. The thickness and strength of the wall kept horizontal movement during construction within acceptable limits, without the need for additional propping. Ground movements were modelled beforehand with a full 3D non-linear finite element analysis, and carefully monitored during construction.

Some 260 cylindrical hollow steel piles, generally of 900 mm to 1900 mm diameter, were then sunk from the level two basement deep into the Thanet Sands some 40 m below ground. The soil inside each pile was excavated down to below the lowest basement level, and steel box-section plunge columns of up to 600 mm x 600 mm were lowered down inside, and concreted into the piles at the bottom. Upward construction could then commence, supported by the plunge columns. Meanwhile, as the lower two basements were excavated the cylindrical steel pile casing could be removed and the exposed plunge columns encased in concrete.

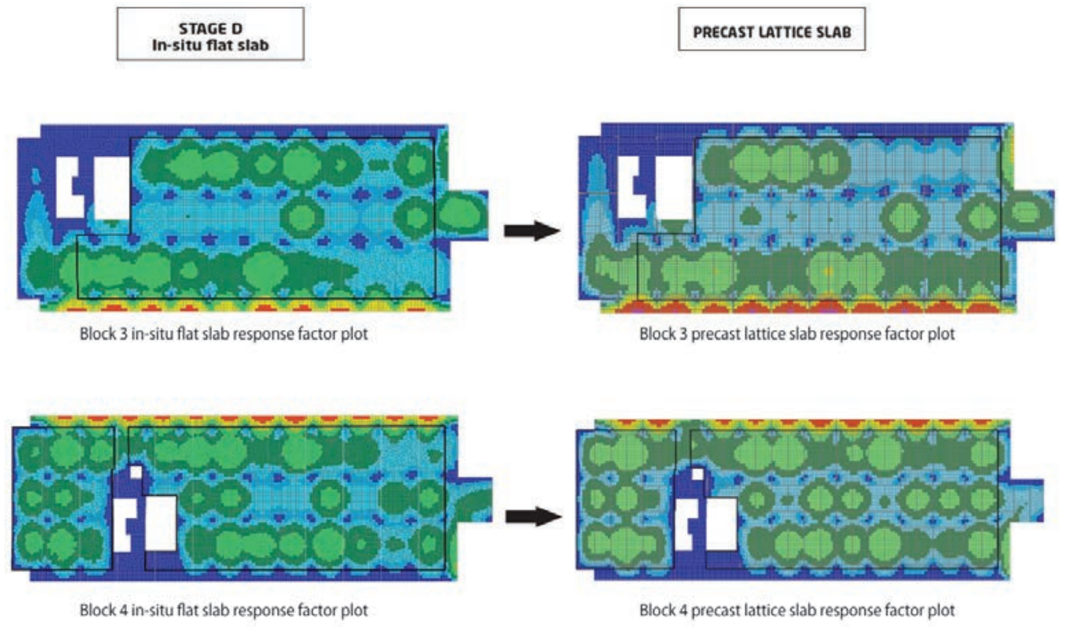
PROTECTED RESEARCH EQUIPMENT

However, much of the research equipment is very sensitive to electromagnetic emissions. Most sensitive of all are the five nuclear magnetic resonance (NMR) spectrometers, which can help determine the details of the electronic structure of molecules by measuring the intramolecular magnetic field. Because of their weight and the need to minimise vibration (see 'Vibration' box), these had to be located deep in the basement. Located close by are two similar but smaller magnetic resonance imaging (MRI) scanners and various super-resolution imaging microscopes, electron microscopes and cryo-electron microscopes (similar, but where samples are studied at cryogenic temperatures). Sources of radiation that could affect these instruments included railways and traffic, radio and TV broadcasts, lifts and the engineering plant. Mitigation measures included shielding the equipment rooms with aluminium, additional active cancellation systems, and filtering all power supplies entering the rooms.

In a typical biomedical laboratory in a less urban location, the sensitive equipment might be housed in a light, single-storey building. In the Crick's basement, the equipment rooms are surrounded by a heavy structure packed with steel to support a multi-storey building overhead, with high magnetic permeability that had to be reduced. Consequently, in these areas, conventional reinforcing steel in the concrete floors and walls was replaced with epoxy-coated stainless steel, which has much lower magnetic permeability, and all secondary steel (such as purlins to support ceilings) was replaced with inert materials such as fibre-reinforced polymers.

This still left the problem of the heavy steel plunge columns close to the spectrometers. The solution, devised by contractor Laing O'Rourke, was to replace the conventional steel columns with precast concrete plunge columns incorporating austenitic stainless steel reinforcement, which reduced the magnetic permeability by a factor of around 100. At 14 m long and weighing 15 tonnes, these were the largest ever manufactured

VIBRATION



Results of the vibration analysis of the floors, comparing the response of an originally planned *in-situ* concrete flat slab (left) with the as-built precast lattice slab © Arup

The Francis Crick Institute has been constructed with a remarkably high resistance to vibration, but the NMR and MRI scanners in the basement required an additional level of protection.

Modern laboratory equipment can accept only extremely low levels of vibration transmitted within the building structure, and the design team agreed early on with the scientists to provide a high Vibration Criteria-A (VC-A) level across all laboratory floors, to allow maximum future adaptability. This limits the vibration threshold to just 50 microns per second – approximately 16 times stricter than the typical limit for commercial spaces. External sources of vibration such as road traffic and trains were measured at ground level before construction: analysis suggested that the sheer mass of the building with its deep basement would absorb most of this movement, and this was confirmed by measurement after construction. All internal sources of vibration were identified and mitigation provided. For example, all engineering plant that could generate vibration has been isolated from the structure by means of anti-vibration mountings, spring hangers and supports. This left the vibration caused by people moving round the building as the most significant factor for the design of the structural slabs, and various combinations of footfall with singles or groups, fast or slow walking, were analysed. The greatest single measure to reduce the effects was to design a heavier and stiffer structure than would be needed for loading alone – for example, concrete floor slab thicknesses are 400 mm minimum rather than 300 mm.

A huge complication came from the decision by main contractor Laing O'Rourke to prefabricate as much as possible of the concrete structure, rather than building *in situ*. This had clear advantages in terms of programme, cost and the quality control that could be achieved in an off-site factory environment, but meant that the vibration response of the structure could be critically affected, particularly by the location of joints between precast units and the form of the joints. Never before had this technique of precast construction been proven in a facility with such stringent vibration limits.

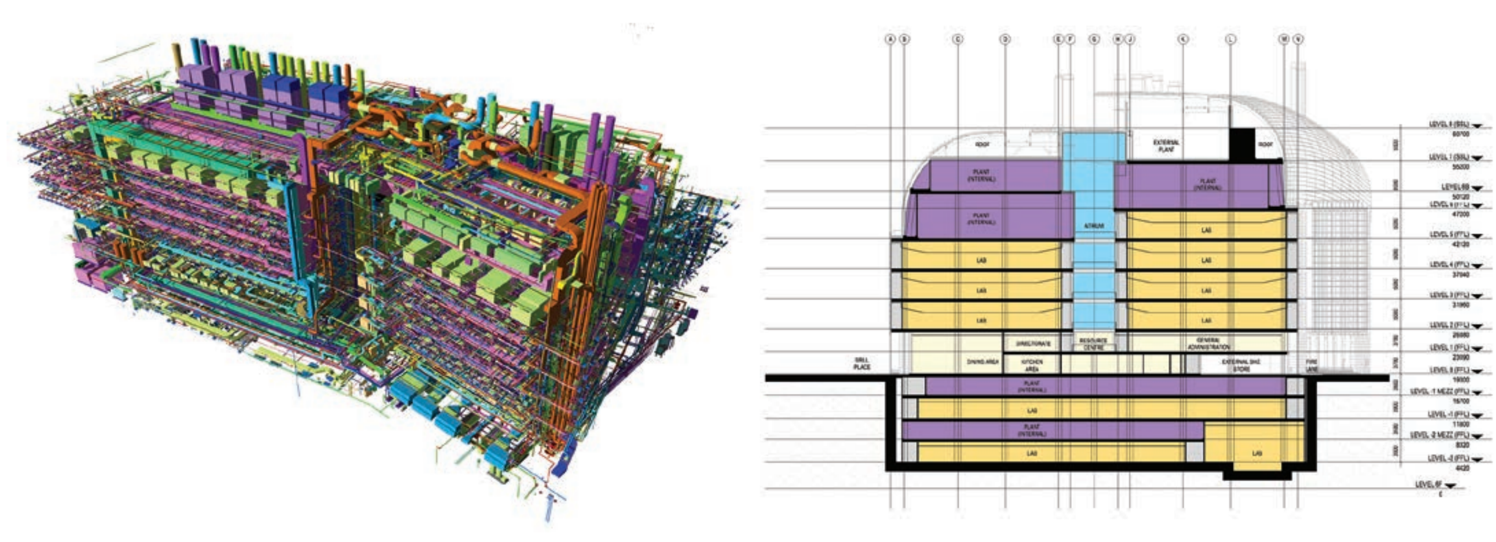
A rigorous modelling exercise was carried out using a combination of analysis software and in-house interface coding to prove that the vibration limit could be met. Different support conditions, damping effects and ranges of applied modes were tried out with alternative mesh densities and material properties to balance the theoretical results with an expected reality.

Results suggested that while the precast behaved in a similar way to the *in situ*, there was generally a slight decrease with the precast in the structure's ability to resist vibration, so further detailed design using finite-element analysis was carried out to reverse the trend. Measures adopted included tailoring the precast detailing and interfaces to align with the behaviour of the building's structural frame, optimising the layout of panels, fully grouting all joints, and maximising the concrete strength.

The highly sensitive equipment in the basement, such as the NMR spectrometers, required far higher levels of vibration protection: up to VC-F, which is more than 15 times as strict as VC-A. The basement floors are stiffer than those at upper levels, but nevertheless the equipment needed special mountings to achieve the required levels. Each NMR sits on a heavy mass-inertia concrete base supported by a tuned spring system, to isolate it from any movement of the basement structure.

off-site and they were so successful that precast is likely to replace steel for plunge columns on some future projects, even where magnetic resonance is not important.

The sophisticated equipment in the lower basement level also posed another complication. At the heart of each of the five NMR spectrometers is a liquid-helium-cooled superconducting magnet, with the liquid helium held in a vacuum at cryogenic temperatures. In the unlikely event of a failure of the vacuum, the helium would 'quench', vapourising to gas at nearly 800 times its liquid volume over a short period. This would have needed additional large-diameter ducts from basement to roof to provide emergency venting for each spectrometer room. To avoid this, the NMRs have been housed together in a large basement chamber of some 2,000 m^3 that has been designed to safely deal with a quench from any one before the conventional air-handling system takes over.



A three-dimensional building information model of the complex and extensive engineering services, so that the building resembles a massive industrial plant with some working space sandwiched in between. As the cross-section through the building shows, two of the four basement levels and three of the eight above-ground levels are mainly filled with services © Arup

FOCUS ON AIR HANDLING

As the cross-section through the building and the 3D services model reveal, the building is packed with engineering services. Two of the four basement levels and three of the eight above-ground levels are almost entirely filled with services, and indeed the building resembles a massive industrial plant with some working space sandwiched in between.

Dominating the engineering services are the air-handling facilities. The units on the upper floors suck in some 400 m^3 of fresh air per second and discharge through an array of stacks along the spine of the building – equivalent to emptying an Olympic-sized pool in less than 10 seconds. The BRF area in the basement has particularly high ventilation requirements, driven by a combination of conditions for hygiene and heat dissipation: some 20 air changes per hour have been used, combined with careful contaminant control, provided by a combination of architectural design and the ventilation regime.

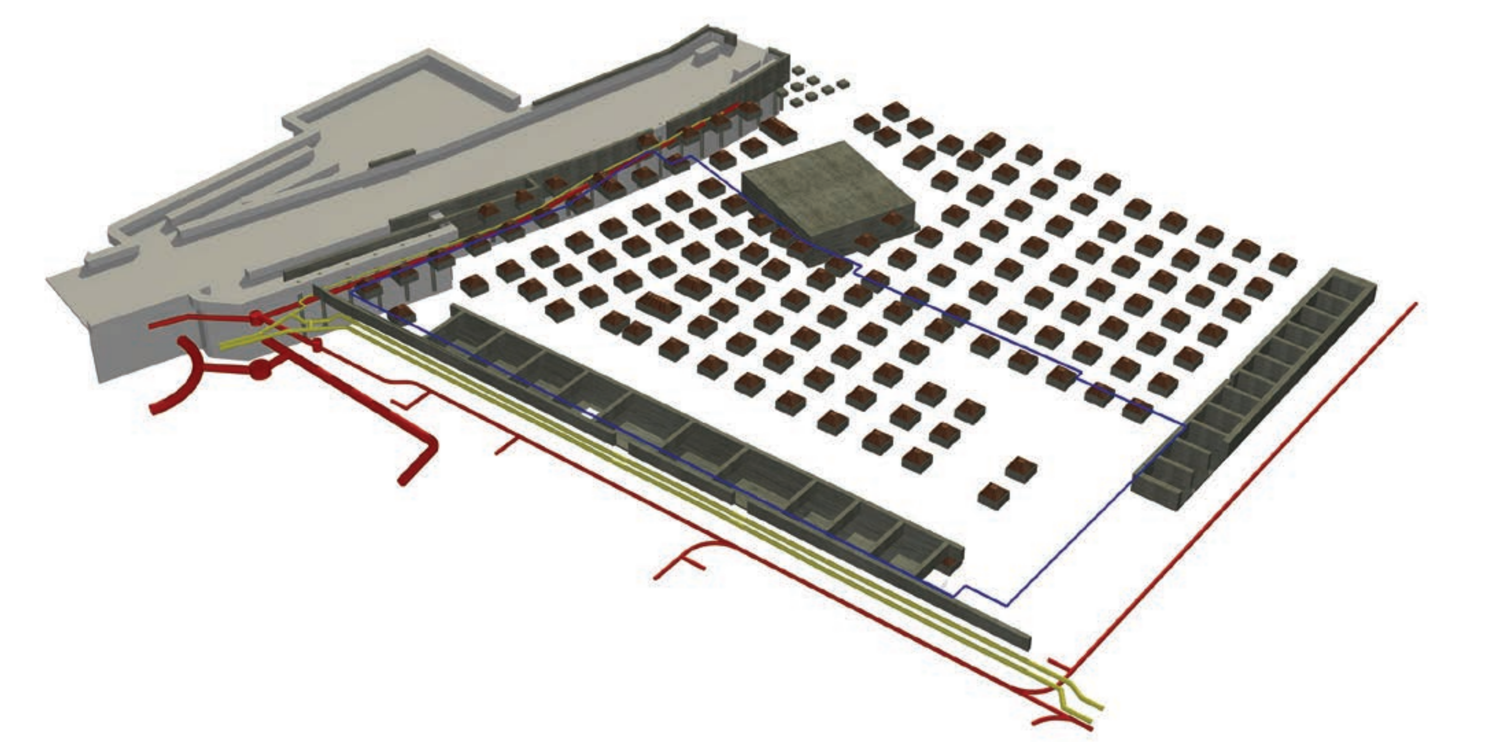
The high-containment laboratories, where for example experiments may be carried out on viruses that are resistant to antibiotics, require particularly rigorous control and are subject to licensing by the Department for Environment, Food and Rural Affairs (Defra). These laboratories are constructed as sealed units within the building structure, with a constant negative air pressure so that any air movement would be fresh air entering the laboratory rather than air escaping, and with high-efficiency particulate arrestance (HEPA) filtration of both air supplies and exhaust. They are subject to strict safety checks by the Health and Safety Executive and must pass rigorous design reviews, called Hazop analyses, as well as quantitative risk assessments for the highest level of containment.

Occasionally these laboratories have to be fumigated, which is achieved by the most effective means known: a 40% solution of formaldehyde in water is boiled in the room, killing all germs but at a concentration more than a hundred times higher than the fatal dose for humans. Careful control of the process, including the safe dilution and exhaust of the gas, is clearly critical. In particular, stainless steel ductwork is used, with torqued gaskets at joints to prevent any leakage.

With such large volumes of air being discharged, emissions from the stacks carrying the exhaust air have been numerically modelled, as well as the flue discharges from the gas- and oil-fired boilers and the building's combined heat and power (CHP) generators. Discharges must satisfy both the Clean Air Act 1956 and the local authority with regard to contamination at local street-level receptor points. A physical model was tested in a wind tunnel to check that no discharges are returned into the building. This combination of numerical modelling, wind tunnel testing and physical measurement was a novelty at the time the building was being designed, though careful planning of discharges from buildings has become more common since.

ENGINEERING THROUGHOUT

Air handling was not the only complication in the engineering services. For example, water had to be supplied in different forms: domestic hot and cold water; separate laboratory hot and cold water; softened water for autoclaves and other sensitive equipment; reverse osmosis water; blended softened water; on-floor treated water



The site was constrained on all sides, with the buried structure of St Pancras Thameslink platforms to the east (left of picture), two Victorian cast-iron gas mains to the north, old brick-arch sewers to the north and west, and the British Library's buried pumping station to the south. The site itself was once a railway goods depot, and was underlain by a grid of brick footings on mass concrete which had to be removed © AKT II

supplies; and, in the BRF area, a specialist aquatic life-support system. Similarly the main gas supplies include liquid carbon dioxide to provide gaseous CO_2 throughout the building, liquid nitrogen and compressed air, and a network of gas manifolds provide flexibility of specialist gas provision. Consequently, the 'plumbing' of the building is exceptionally complex, requiring (in addition to the plant floors) large vertical distribution risers running the height of the building, with horizontal primary routes for services connecting between risers at each floor level. A state-of-the-art building information model (BIM) was used to coordinate services runs and minimise clashes, led by the building's principal architect, HOK.

Many of the building's systems are duplicated or backed up to provide additional security. If the power and gas supply fails for the whole building and diesel deliveries are suspended for the dual-power boilers, the building is designed to run fully for two days, followed by a gradual controlled rundown – an unusually strict fail-safe procedure governed by the Home Office. This requires a 7.5 MVA standby generation capacity, and a 300,000-litre diesel fuel storage.

Visitors to the Crick may appreciate the striking architecture of the building with its geometric terracotta blocks topped by two flowing, overlapping curved steel roofs, or they may wonder at the cutting-edge research being carried out within. However, very few will comprehend the extraordinary engineering that has gone into its construction.

BIOGRAPHIES

Steve Berry is an Associate Director at Arup and Building Services Design Team Leader for The Francis Crick Institute, where he is responsible for the delivery of the mechanical, electrical and plumbing (MEP) systems. Steve joined Arup in 1988 and obtained a degree in engineering in 1992. Since that time, he has worked with the firm in Germany, Russia, Thailand, USA and Denmark.

Rob Partridge is a Director at structural and civil engineering practice AKT II, and is responsible for leading a diverse range of projects, both in the UK and internationally. His portfolio includes: The Francis Crick Institute with HOK International and PLP Architecture; the Eli and Edythe Broad Art Museum, USA, with Zaha Hadid Architects; and the Whiteleys development in London with Foster + Partners.

THE PROJECT TEAM

Client: **Francis Crick Institute**
Project manager: **Arup Project Management**
Architects: **HOK, with PLP and BMJ**
MEP engineer: **Arup**
Cost consultant: **Turner & Townsend**
Structural engineer: **AKT II**
Main contractor: **Laing O'Rourke**

From keel to masthead, the HMS Queen Elizabeth towers 56 m in height and the overhanging hull supports a flight deck covering 4.5 acres © Aircraft Carrier Alliance

BUILDING BRITAIN'S BIGGEST WARSHIPS

The 1998 Strategic Defence Review called for the UK Armed Forces to be able to operate with more agility to confront situations on a worldwide basis and resulted in the requirement for two new Queen Elizabeth Class aircraft carriers, HMS Queen Elizabeth and HMS Prince of Wales. Richard Gray, freelance technology journalist, talks to Martin Douglass, the Aircraft Carrier Alliance's Chief Engineer, about the challenges involved in one of the UK's largest engineering projects and the innovative way in which the carriers came together.

Standing beneath the enormous curving hull of the new HMS Queen Elizabeth, it is easy to summon the spirit of Britain's mighty naval past. The ships that once glided into the water from dockyards around the country enabled this small island to become a naval superpower that dominated the oceans.

Today, Britannia may not exactly rule the waves anymore, but this does not mean its time as a great seagoing nation has come to an end. The UK is still an island nation, and roughly 95% of the country's economic activity still depends on the ocean, according to figures from the Royal Navy.

Britain is currently undertaking the most ambitious shipbuilding project it has ever attempted. The HMS Queen Elizabeth and HMS Prince of Wales aircraft carriers are the largest warships to ever be constructed in Britain.

Weighing more than 65,000 tonnes each, they are more than three times the weight of the old Invincible Class aircraft carriers that they are replacing. After nearly 16 years of planning and construction, HMS Queen Elizabeth is almost complete. In 2014, it was moved from the dock in Rosyth, Fife, to a nearby jetty where it is now having the final equipment installed.

It is an impressive sight. From keel to masthead, HMS Queen Elizabeth towers 56 m in height, taller than Niagara Falls in North America. The overhanging hull supports a flight deck covering 4.5 acres – more than two and a half times the size of the pitch at Wembley Stadium.

Floating in the non-tidal basin at Rosyth Dockyard, HMS Queen Elizabeth's propulsion and radar systems are currently being set to work. The crew is due to move on board at the beginning of 2017, ahead of

The view of the bow from underneath HMS Prince of Wales, currently undergoing assembly in Rosyth © Aircraft Carrier Alliance

Now structurally complete and fitted out, HMS Queen Elizabeth is undergoing final commissioning in Rosyth, Fife
© Aircraft Carrier Alliance

sea trials a few months later. Yet getting to this point has involved a monumental feat of engineering. Initial design work for the Queen Elizabeth Class aircraft carriers began in 1999, following the Strategic Defence Review the previous year. This had underlined the need for more agile and flexible armed forces to cope with the diverse threats the UK now faces. The aircraft carrier was seen as being central to delivering this capability.

To provide this new flexibility, the ships have been designed with a series of innovative features and new technologies. Perhaps most distinctive is the 'twin island' approach that has separated the bridge and flight command centres.

Rather than the traditional single tower on the flight deck used on all other aircraft carriers in the world, HMS Queen Elizabeth and HMS Prince of Wales have two separate command towers: the forward island houses the bridge, while the aft will be responsible for air operations and air traffic control.

This innovative design provides two key benefits. First, it makes the vessel far more resilient to damage as each island is designed to switch functionality, meaning if one is put out of action, the other can be used to perform both roles. Inside each are multifunction screens that can provide all the information needed for running the ship. Separating the command nodes in this way also gives the flight command, or FLYCO as it is known, an unhindered view of the flying operations.

Each of the 30 m high islands has also been designed to reduce the radar signature it generates. While it is virtually impossible to hide a vessel the size of an aircraft carrier – particularly when it has two large aircraft lifts on the side – the external panels on the islands are angled to deflect radar signals, drawing on some of the lessons learned from the Type 45 destroyers they will eventually operate alongside.

Another of the lessons learned from the Type 45s was in the process of constructing the vessels themselves. The bows of these cutting-edge destroyers were built at a separate shipyard to the rest of the vessels before later being slotted into place.

CONSTRUCTION ACROSS SIX SITES

With a project as large as the Queen Elizabeth Class aircraft carrier programme, it was clear that no single shipyard was going to be large enough to build the ship in its entirety. So rather than using the traditional keel-up approach to shipbuilding, the aircraft carrier was divided into blocks that were constructed at different shipyards around the country before being brought together at Rosyth.

In all, six separate shipyards owned by four different companies have built major sections of HMS Queen Elizabeth, and subsequently HMS Prince of Wales. Rosyth was chosen as the yard where the ships were assembled, as its dock was the only one big enough to take the vessels. A 68 m tall crane – with the biggest lift capacity in the UK at 1,000 tonnes – was

Each of the aircraft carriers have been built in blocks at separate dockyards around the UK before being brought to Rosyth to be pieced together. Massive sections of the aircraft carrier were 'skidded together' with millimetre accuracy. This world record saw 25,000 tonnes of ship moved back more than 17 m © Aircraft Carrier Alliance

commissioned specifically for the project.

Standing in the empty dock is an intimidating exercise – the huge open space between the dock walls and gate tower above gives a sense of the sheer pressure of water being held back. As the segments of first HMS Queen Elizabeth, and then later HMS Prince of Wales, were gradually assembled, the almost agoraphobic sensation of the dock was replaced with a feeling of claustrophobia as the vast steel structures blocked out all natural light beneath the 280 m long and 73 m wide vessel.

Each of the enormous segments of the aircraft carriers, built from a total of more than 100,000 tonnes of steel, needed to be precisely engineered to identical standards to ensure every section of deck, every corridor, every doorway and every bolthole lined up. To help ensure this, 3D computer-aided design systems were used to build a virtual prototype of the entire ship that was then used across the entire supply chain.

Delivered to Rosyth by barge, the blocks were pieced together like a giant 3D jigsaw puzzle. The dock itself could be separated into sections, allowing just parts of it to be filled with water, so that the segments could then be floated into place.

Installing the largest section of each vessel – an 11,500-tonne piece known as lower block four – meant flooding half of the dock while the bow half of the vessel remained dry behind a removable gate. The new block was floated into place before the water was removed and the 25,000-tonne bow segments were skidded back to meet the new piece.

Bringing these sections together was only the beginning. There is a significant amount of welding needed to make the pieces structurally complete and then to join up the services, such as heating, ventilation and air conditioning, pipework and electrical cables. To turn these fitted-out blocks into working warships requires about 18 months of fit-out and commissioning.

ENGINE POWER

Powering each carrier are two Rolls-Royce MT30 gas turbines and four diesel generators capable of producing a combined power output of 110 MW, enough to power a large town. This is used to drive the vessels' electric propulsion system through twin shafts, each with two 20 MW general electric motors that can be operated individually or in tandem to achieve a maximum speed of 25 knots.

At the end of each shaft sit 33 tonnes of propeller, designed with five blades that can have their pitch angle adjusted to match the speed requirements of the vessels as they are upgraded through their lifetime. Individual blades can also be replaced underwater if they become damaged, reducing the need for the vessel to be dry-docked.

Each nickel-aluminium bronze propeller delivers around 50,000 horsepower, yet, unusually, they have been designed in tandem with the twin rudders so they can work together to increase the torque they produce in the water.

The rudders themselves have been given a twisted design to help reduce the vibrations that can occur as bubbles produced by the spinning propellers collapse onto their metal surface – an effect known as cavitation ('Quieter, more efficient propellers', *Ingenia* 65).

An enormous bulb on the bow beneath the waterline will also help ensure that the huge vessels can slip through the water more smoothly.

JOINED-UP SYSTEMS

Inside HMS Queen Elizabeth, more than 320,000 km (198,838 miles) of electrical cables and

Inside HMS Queen Elizabeth, more than 250,000 km of electrical cables and 8,000 km of optical fibres have been installed to link up the networks of communications, control and IT systems on board

Each of the aircraft carriers is powered by two Rolls-Royce MT30 gas turbines and four diesel generators, which together produce a combined output of 110 MW. One of the MT30 gas turbines is pictured above © Rolls-Royce

Two 33-tonne propellers, one of which is pictured above, will drive HMS Queen Elizabeth and HMS Prince of Wales through the water. They have been designed so their pitch can be modified to aid propulsion through the water © Rolls-Royce

8,000 km (4,970 miles) of optical fibres have been installed to link up the networks of communications, control and IT systems on board.

Splitting the command between two islands has meant that the same information about the propulsion system, the radar, the weather, the wind, and the ship's heading and speed, together with all communications, need to reach both at the same time. Additionally, an operations room deep within the ship also needs to be linked to this same set of data.

To achieve this, a novel, integrated system has been developed to communicate information throughout the ship, split between an administrative network, a system that controls the ship and a third protected system that is responsible for the management of the aircraft, onboard sensors and weapons systems.

Technology has also helped to deliver another key requirement for these modern aircraft carriers: allowing fewer crew members to achieve more. With a crew of just 679, HMS Queen Elizabeth will have just 29 more in its company than the much smaller Invincible Class aircraft carriers. When fully laden, it will be carrying 36 of the new F-35B Lightning II aircrafts and four Crowsnest helicopters, along with nearly 1,000 air crew.

Much of this is made possible by an innovative munitions handling system. In what is the first naval use of a system more commonly seen in land-based warehouses. The highly mechanised weapons handling system moves pallets of munitions from the magazines deep in the ship to a weapons preparation area and then onto the flight deck where they can be fitted to the aircraft.

It works much like the robotic systems used in modern large-scale logistics centres, where orders are moved around by machine before being packaged.

The system on the Queen Elizabeth Class aircraft carriers, housed within a supermarket-sized area, uses 56 'moles' that lift and move a payload along a complex network of rails fixed throughout the ship.

Thanks to the moles, the ship's magazines are completely unmanned and are instead controlled from a central location. The moles themselves have been designed so that two different versions work in tandem: one to traverse forward and aft, and another that moves between port and starboard. The two types are different shapes to

HMS Queen Elizabeth, illustrated above alongside the new Type 45 destroyer, will become the nation's flagship alongside HMS Prince of Wales
© Aircraft Carrier Alliance

allow the packets of munitions to be lifted and carried in the correct orientation.

Each mole has a predetermined area of travel, and they can transfer payloads between each other, transporting the weapons from the magazine to the preparation area in a kind of moving mechanised version of pass the parcel.

Electrical lifts and drives ensure that the potentially dangerous pallets are precisely stowed and positioned as they are moved. A series of lifts connect the magazines to the hangar, weapons preparation area, and flight deck, and a unique mechanism enables the mole to access the lift platform without needing to disengage and re-engage from the rail system.

Yet it is not just the handling of weapons that has allowed the crew to be streamlined and freed up for other duties. Even the ship's four galleys have been specifically designed to allow food to flow from storage, through the preparation areas to cooking and onto plates as quickly and efficiently as possible. Just 67 catering staff will be able to feed the entire ship's crew and the largest galley has the capacity to serve 960 crew members in just one hour. To ensure the crew has a supply of fresh water while at sea, a £1 million reverse osmosis system will draw in sea water and produce 500 tonnes of fresh water a day.

Unlike any other ship in the Royal Navy, HMS Queen Elizabeth even has its own bakery on board, capable of producing 1,000 loaves of bread a day. The crew will be able to start and end their day with the smell of fresh bread wafting from the bakery as they arrive at the dining halls.

Many systems onboard – even down to the waste handling system – have been automated as much as possible to reduce the burden on the crew. The vessel has an expected lifespan of 50 years, so there has also been an emphasis on ensuring the technology on board is at the cutting edge. Unlike the old aircraft carriers, the Queen Elizabeth Class will be making extensive use of wireless communications throughout the vessel to allow the crew and the teams on the flight deck to move around with their hands free.

These wireless communications are provided using terrestrial trunked radio (TETRA), which can communicate directly and via base stations. Around 500 handsets will be provided for above- and below-deck communications for mobile teams.

The majority of the communications on board will be handled by a tactical command and control voice system (TC2V), while there is also a voice over IP system and

To cope with the extreme heat generated by aircraft engines, a new type of coating has had to be developed to protect the decks. Normally the flight decks of aircraft carriers are coated with an anti-slip paint to prevent aircraft from losing control as they take off and land, while also keeping the crew safe

183 self-powered telephones to provide a backup should the other systems fail.

Their modular design will also help the vessels to stay up to date as they age. In 50 years, technology can change dramatically – just look at the 40-year evolution of the desktop computer into handheld devices that fit into our pockets.

In both HMS Queen Elizabeth and HMS Prince of Wales, redundancy has been built into areas of the vessel where new equipment can be installed as technology progresses.

Each vessel will carry 36 of the new F-35B short take-off and vertical landing jets. The exhaust jet produced by these aircraft has meant engineers have had to develop an entirely new deck coating to protect it from the extreme heat
© Aircraft Carrier Alliance

FIT FOR AIRCRAFT

On the flight deck, there is the ability to install catapults and restraint cabling should the aircraft onboard also change. HMS Queen Elizabeth is due to carry the short take-off and vertical landing version of the F-35B supersonic stealth jets, and so it has a ramp built on the front of the platform. Fitted with an engine that can swivel 90 degrees and a LiftFan engine under its belly, the F-35B can take off and land without the need for any assistance.

However, early in the vessel's design, there was an expectation that it might have been equipped to carry the normal version of the F-35, which requires a catapult and restraining system to prevent it from pitching over the side into the sea, and so there are still spaces on the deck, and internally, where these could be accommodated in the future.

To cope with the extreme heat generated by aircraft engines, a new type of coating has had to be developed to protect the decks. Normally the flight decks of aircraft carriers are coated with an anti-slip paint to prevent aircraft from losing control as they take off and land, while also keeping the crew safe.

The jet exhaust gases from the F-35B, which can reach temperatures of more than 920°C, have been found to quickly degrade the standard coatings, so an experimental non-skid thermal metal spray is being used in key areas of the deck to protect it.

This is a layer of molten metal that bonds to the deck as it cools and provides a raised surface to prevent skidding. However, it needs to be applied at exactly the right rate and temperature to ensure that it sets properly. When applied correctly, the coating helps to dissipate the heat produced by the F-35B exhausts and means that the deck will be more resilient.

Although thermal spray has been used before to protect vessels while at sea, on the aircraft carrier it had to combine heat-resistant properties with the drop needed on a flight deck.

A specialist firm, Monitor Coatings, based in North Shields, Tyne and Wear, was awarded the contract to develop the coating, which will ultimately cover more than 19,500 m^2 of deck. Many different methods were tested extensively at BAE Systems' hot gas laboratory in Warton, Lancashire.

The exact formulation of the metal spray is still a closely guarded secret. It was applied using a specially developed low pressure plasma-spraying technique, where powdered metal is fired through a jet of plasma at temperatures of almost 10,000°C (18,000°F) onto the deck.

When fully powered, HMS Queen Elizabeth will be able to track 1,000 aircraft simultaneously up to 250 miles away

Many of the larger blocks, which have been fitted together like a jigsaw to build each vessel, weighed in excess of 11,000 tonnes and required the world's biggest submersible barge to transport them around the UK to Rosyth, Fife

The molten droplets then flatten and quickly solidify, creating a tough and rough coating 2 to 2.5 mm thick, bonded to the steel beneath. This can provide grip and also cope with the extreme temperatures created by the F-35B exhausts.

In addition to the deck, there are a staggering 370 acres of vessel that have needed painting to help protect the steel from the corrosive ocean environment.

NAVIGATING THE SHIP

As the crew prepares to take over the HMS Queen Elizabeth, it has already started moving equipment into some of the vessel's 3,011 compartments. Such is the size, it is easy to become lost in its warren of compartments in the nine decks below the flight deck level. A special platform navigation system has been installed to help those onboard find their way around.

Standard satellite navigation signals cannot penetrate the steel hull, and with many of the compartments hidden deep within the ship away from any windows, another approach was needed.

Quick response (QR) codes have been installed at key points around the vessel so that they can be scanned with a handheld device such as a tablet or a smartphone. Combined with the deck plans and route-finding software, this can reveal a person's location on the device, and work like a vessel-wide GPS to guide people to where they need to be.

While the new crew will be able to use familiar ship location markings to find their way around, this positioning system also proved vital during construction to prevent workers from getting lost while fitting out the ship.

This technology could also find uses beyond the Queen Elizabeth Class carriers – helping people to navigate large environments such as underground transport networks or even hospitals.

OUT AT SEA

HMS Queen Elizabeth is almost ready to leave on its first voyage. The vessel's two 13-tonne anchors have also been tested for the first time, and its radar has begun turning and has already been tracking aircraft on approach to Glasgow airport, 40 miles to the west of Rosyth. When fully set to work, it will be able to track 1,000 aircraft simultaneously up to 250 miles away.

Ultimately, when it becomes fully operational in 2020, the aircraft carrier will be a home to more than 600 people and a temporary home to a further 1,000. While on board, they will all live, work and potentially fight alongside one another for months at a time. HMS Prince of Wales is due to become operational shortly afterwards in 2023.

Much like the crews of the great Royal Navy warships of the past, those serving on board will be responsible for ensuring the security and livelihood of the British nation for years to come.

BIOGRAPHY

Martin Douglass is Engineering Director at the Aircraft Carrier Alliance and Chief Engineer of the Queen Elizabeth Class aircraft carrier programme. He has previously worked in marine engineering for BAE Systems and the Ministry of Defence, having completed a Bachelor of Engineering in the field. He also holds an MSc in defence acquisition from Cranfield University.

When he signed up to be a Royal Academy of Engineering Visiting Professor in sustainability at Aston University, Keith Clarke CBE HonFREng decided to think big. He organised Carbon Week, a series of lectures, events and student projects to engage all of the university's second-year students in the challenges represented by climate change and to alert them to the 'phenomenal entrepreneurial opportunity' that it offers to young engineers © Aston University

AN INTRODUCTION TO THE 'REAL WORLD'

Graduates can emerge from university with little face-to-face contact with engineers who have worked in industry. To counter this shortcoming, leading engineers are going back to university as Royal Academy of Engineering Visiting Professors to give undergraduates a frontline view of engineering. Science journalist Michael Kenward OBE talks to some of the Visiting Professors about their experiences of the scheme.

It was something of a job share for Sam Beale, Pieter Knook and Rick Mitchell (L–R) when they became Visiting Professors in the engineering department at Cambridge University. The trio brought experience from different industries to their roles, including small start-up businesses and major engineering companies in aerospace and electronics. One result of their work is a new course on 'The Engineer in Business', which Mitchell says will give students insights into how to get things done © Cambridge University Department of Engineering

It was carbon awareness overdrive at Aston University in November 2015. Keith Clarke CBE HonFREng, Royal Academy of Engineering Visiting Professor in sustainability, had invited all second-year students to immerse themselves in Carbon Week – a series of lectures, masterclasses and other events. He wanted to "bring climate change awareness and low-carbon design thinking" to all of Aston's students. With more than 1,500 students participating in the week's first-day conference, the event made waves on social media.

Clarke's plan was in line with the broader aims of the Academy's industry-into-academia initiative, which sets out to 'utilise the experience of the Visiting Professors to enhance student learning as well as the employability and skills of UK engineering graduates'. When it came to Carbon Week, Aston saw it as a way of exposing students to what could be an important career opportunity, and the students themselves found it to be a valuable experience. As one student put it: "[It was] ultimately beneficial and puts us ahead of the game on something that may sooner or later become a global crisis."

VISITORS WITH EXPERIENCE

The Academy's Visiting Professors (VP) scheme exposes students to the real-world experiences of senior engineers in industry. Without this sort of interaction, students may only encounter academics in their undergraduate learning. VPs pass on their experiences in many ways. An informal introduction to the scheme, *The rough guide to being an Academy Visiting Professor or Visiting Teaching Fellow*, lists some of the things that VPs get up to, including "developing and delivering new lectures or even whole modules, preparing material (such as case studies) for others to deliver, tutoring or mentoring students, running activities such as an industrial advisory board or industrial visits, acting as an external judge for Dragon's Den-type activities, advising on curriculum development, proposing and/or supervising undergraduate projects and many more".

Only a superhuman VP could do everything on this list; after all, their academic work goes on in the day or so a month that they take out from their jobs in industry over the three years of their appointment. However, many VPs cram in plenty of activities. For example, Rick Mitchell, VP in innovation, spent time at Cambridge University where, as he puts it, he did "quite a bit of teaching", alongside coaching sessions on how to make presentations to future employers and stakeholders, especially companies, and judging at student entrepreneurship competitions: "We helped a lot with a student group project involving designing a

During his time as a Visiting Professor at Cambridge University, Rick Mitchell's role involved helping a student group to design a robot, as well coaching students to make presentations © Cambridge University Department of Engineering

The Academy appoints a new cohort of VPs each year, and since the scheme started in 1989, more than 200 VPs from around 50 companies have worked in 60 universities across the UK

robot." Embedding VPs into the department helps them feel interested in the relationship they have formed and encourages them to strengthen it once their time as a VP has finished. Sustaining these relationships between industry and academia is one of the major aims of the scheme.

Mitchell's experience also showed that VPs can influence what universities teach. "We also researched and proposed a new compulsory module in the second year of the main course, called 'The Engineer in Business'." This follows on from Cambridge's first-year course, 'The Engineer in Society'. The new course, planned to start in 2017, will "give students some insights into how to get things done", says Mitchell. "Innovation is not just invention but also the selection of what to do; justifying and persuading; project management; understanding and working with other functions; and turning an idea into reality." Mitchell brought to this course experiences from a career that has taken in jobs such as Group Technical and Quality Director at Domino Printing Sciences and senior roles in different parts of Philips Electronics.

Mitchell's professorship may have had more impact than some because it was organised as a jobshare. "The unusual thing about my experience was that there were three of us sharing the position," he says. His partners as VPs were Pieter Knook and Sam Beale. "This was actually very successful," says Mitchell. Knook brought experience from various roles in technology start-ups, while Beale had been Head of Technology Strategy at Rolls-Royce Group.

Like the Cambridge trio, most VPs tend to concentrate on their own expertise, the university's needs and where they can have an impact. For example, one VP dedicated their time to working on one of the notoriously complicated challenges that face universities: how do they find common ground with or even find SMEs?

Keith Clarke's career experience with Atkins, as Director of Sustainability and former Chief Executive, meant that he was able to give students at Aston University insight into what businesses really want from new graduates
© Aston University

DRAWING ON INDUSTRY EXPERTISE

The Academy appoints a new cohort of VPs each year, and since the scheme started in 1989, more than 200 VPs from around 50 companies have worked in 60 universities across the UK. The current roster has nearly 60 VPs from over 40 companies working in 33 different universities. Companies and organisations that have supported the scheme include Arup, Rolls-Royce, Ford, IBM, QinetiQ, Scott Wilson, and the Defence Science and Technology Laboratory (Dstl). Feedback from Liverpool John Moores University, which hosted Ron Bell from Engineering Safety Consultants Ltd, suggests that the experience on offer is very much welcomed: "More than 100 students have benefited from the VP's contribution to improving three core modules. Many students said that it was very useful to have more industrial flavour in their engineering degree studies."

In Clarke's case, his time at Aston came after a career with Atkins, which needs to recruit engineers who can 'think carbon'. He organised Carbon Week partly to alert Aston's students to the problems that they will face owing to climate change, but to also alert them to the "phenomenal entrepreneurial opportunity" that it offers to

Dr Dorte Rich Jørgensen, a sustainability consultant engineer with Atkins, underlined the value of industrial contacts during her time as a Visiting Professor in innovation in the School of the Built Environment at Heriot-Watt University. As well as helping to shape the university's strategic development plan, along with courses for the architectural engineering department, she was a speaker at the university's annual Industry Day
© Dr Dorte Rich Jørgensen

young engineers. Aston's Vice Chancellor Julia King DBE FREng, Baroness Brown of Cambridge, explains that students take his message seriously because of his background: "He is very persuasive because he comes from the world of business – he can say that business really needs this, this is what business really wants its new graduates to know about, and be able to think about in the context of their jobs and the company's business."

Hugh Varilly also wanted to inject entrepreneurial thinking into his time as a VP in innovation at University College London (UCL). Varilly brings a lifetime's experience in the computer sector, mostly with IBM where he was involved in implementing major IT programmes, not to mention fixing them when they went wrong. Once again, few career academics can bring this sort of experience to their teaching. It isn't even the sort of thing that students can read about in textbooks.

As a VP, Varilly says: "I wanted to help bring practical experience from industry into the undergraduate teaching at UCL, and give something back." It turns out that many of the undergraduates that he teaches do have some industry background. As he says, they have done internships or have part-time jobs to help pay their way through university. "What they sometimes lack," he adds, "is a deep understanding of heavy duty IT or business processes, as their internships, while very useful, tend to operate somewhat at a surface level."

Like Varilly and Clarke, Dr Dorte Rich Jørgensen had a clear idea of the message she wanted to get across when she became a VP in innovation at the School of the Built Environment at Heriot-Watt University. Again, she sees climate change as something that students need to think about. "I want to do my bit to ensure that global warming is addressed. I want to influence academia and industry to enable future and current professionals to have the skills and behaviours to be able to do that." So when Heriot Watt called with the idea of becoming a VP, working in architectural engineering and civil engineering, Dr Jørgensen jumped at the opportunity.

Dr Jørgensen is a sustainability consultant engineer with Atkins. She describes her job as being to ensure "that sustainability is embedded within infrastructure and built environment projects, and within our business". One of her tasks as an engineer was as sustainability manager for the Atkins infrastructure design team on the Olympic Park site in East London. It is this experience of making things happen that appeals to students. "The feedback from the students was usually that they were very inspired by what we have made possible in the 'real world'."

A LASTING PARTNERSHIP

The overarching goal of VPs may be to engage with undergraduates, but their work rarely stops there. For example, in 2013, Dr Jørgensen was the industry catalyst when Heriot-Watt University was setting up the Royal Academy of Engineering Centre for Excellence in Sustainable Building Design, a venture that brought together Heriot-Watt, UCL, Sheffield and Loughborough universities.

The university also credits Dr Jørgensen with helping to shape its strategic development plan, as well as courses for the architectural engineering department. Professor Gareth Pender, Head of the School of the Built Environment at Heriot-Watt University, summed up the wider interaction when he said: "The synergy created between Dr Jørgensen and members of our academic staff has led to a number of exciting initiatives in research and teaching that will benefit the school and the wider university." He described the visiting professorship as "easily the most productive visiting professorship in our school to date".

While students and universities are clearly an important part of the relationship with the VPs, as Dr Jørgensen found when she was a speaker at the university's annual Industry Day, there can also be business opportunities. "Creating synergies between industry and academia can lead

Many universities encourage students to spend time with and learn from professors with engineering experience in business to increase their employability. To reinforce this, Aston University also invited employers to send staff to the first day of Carbon Week © Aston University

to business opportunities," she says. "Speaking at events such as Heriot-Watt's Industry Day is a great way of showcasing what we do and how we do it."

Dr Jørgensen's work in promoting collaboration between industry and academia also resulted in a memorandum of understanding between Heriot-Watt and Atkins in high-speed rail. This led to the creation of a new centre at the university that hopes to "push rail track research beyond high speed and towards ultra-high speed".

CAREER PROSPECTS

An important reason why universities welcome VPs is that they can enhance students' career prospects. As much as universities appreciate the opportunity to expose students to professors with engineering experience in business, it can also help them to get jobs when they graduate. Aston University reinforced this message in its pitch to students, and it also invited a number of employers to send staff to the first day of Carbon Week.

Dr Jørgensen also ensured that her students were prepared for the workplace. "I always aimed to [point] them in the direction [of] industry where they would have the best fit for their skills, applying my experience so far and giving pointers to support structures for them." She still maintains links with the university and with her students. "I am so proud every time I watch a Heriot-Watt student succeed!" she says. Another important aspect of her time as a VP was the opportunity to show that women can also make it to senior levels in engineering. "I celebrate how the women at Heriot-Watt reach the top of academia. We have balanced gender representation."

Another way in which students benefit from the presence of VPs is in student placements. One survey of the scheme found that the number of students applying for internships went up at the companies where VPs worked.

Peter Goodhew FREng, who chairs the Royal Academy of Engineering's VP steering group, says that a common thread among VPs is their enthusiasm for working with both students and young staff who lack industrial experience. His favourite anecdote is of a class of students who were asked to come up with a definition of what engineers do. The best answer was "engineers design and make stuff". As he puts it, "I don't think anyone could do better using only five words. The VP scheme helps to explain why and how engineers design and make stuff."

The benefits from the programme do not flow in one direction. For example, companies say that VPs are an important way of letting students know who they are and what they do. In other words, the scheme can help with recruitment in what is an increasingly competitive market for engineering graduates.

Clarke's activities at Aston highlight another contribution that VPs can make at a receptive university. As Baroness Brown puts it: "Because he comes from outside he doesn't accept that things can't be done for university administrative reasons, and he challenges us all the time to move more quickly and be more responsive – a very healthy and positive challenge. We sometimes need to be encouraged to break our own rules inside universities!"

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*.

MACROBERT AWARD 2016

Supported by the Worshipful Company of Engineers

The Royal Academy of Engineering MacRobert Award is the premier prize for innovation in UK engineering. It is awarded annually for an outstanding example of innovation, that has achieved commercial success and is of benefit to society. It seeks to demonstrate the importance of engineering and the contribution of engineers and scientists to national prosperity and international prestige.

The award was founded by the MacRobert Trust and first presented in 1969. Every submission is reviewed by a panel of judges drawn from the Academy's Fellowship and across engineering. The award honours the winning company with a gold medal and the team members with a prize of £50,000. Here, *Ingenia* showcases the three finalists for this year's award in alphabetical order. The winner will be announced at the Academy Awards Dinner on 23 June 2016.

THE WORLD'S MOST INTELLIGENT PROSTHETIC LIMB

BLATCHFORD GROUP

Linx is the first-ever prosthetic limb with integrated robotic control of the knee and foot – a system in which the parts work together like a human leg.

Where previously lower leg prosthetics wearers have had to plan their days meticulously according to the limitations of terrain they can tackle – a walk in the country may be more trouble than it's worth – the smart robotics in the Linx limb system, developed by Basingstoke-based Blatchford, constantly monitor and adapt to movements and automatically adjust to the environment.

INNOVATION

The Linx uses seven sensors across both the knee and foot that act like human nerves, continuously collecting data on the user, activity, environment and terrain. The central computer then acts like the brain, using this data to adapt the limb's response using pioneering software called Mi^2 (motion-integrated intelligence). This means the wearer can walk confidently, knowing that the limb will be at the right speed and support level at all times.

Even simply standing still can be a challenge for lower limb prosthetics wearers, using a lot of energy and concentration to hold the leg steady, which means that severe back pain can be common. The Linx senses when the wearer comes to a standstill and automatically locks so that they can relax, and when they want to move again, the sensors immediately leap into action and unlock seamlessly.

When a patient is first fitted with the Linx, a clinician programmes its central computer by running through a calibration sequence so that the limb learns how its wearer naturally walks and adapts accordingly. This is done via a Bluetooth connection to a desktop programme that shows in real time what the sensors are picking up as it detects the wearer's natural speed and movements. A smart algorithm then calibrates the limb automatically in one simple step as the knee and the foot sensors 'talk' to each other. Previous prosthetics would require each set to be calibrated in turn in a lengthy process that would often require repeat adjustments.

The Linx limb system's sensors act like human nerves to inform the prosthetic's response so that users can walk, balance and be supported on all types of terrain © Blatchford Group

COMMERCIAL SUCCESS

In England alone, there are currently around 45,000 people who rely on prosthetic limbs, with around 4,000 lower limb amputations carried out each year. Currently, only a fraction of these will have access to the latest technology in the Linx as it falls outside NHS budgets; most Linx limbs in use today are benefiting amputees in the USA and Norway. Prosthetic limbs offered by the NHS vary depending on budget cycles within the financial year. Despite a high price point, the Linx may reduce costs in the longer term by reducing secondary treatments required for back pain, arthritis and falls, extending the life of sockets, and in lessening the need for carers by giving amputees more freedom.

BENEFIT TO SOCIETY

Blatchford is a family owned business established in 1890, and has grown to become a global leader in the provision of prosthetic and orthotic products, and in providing specialist treatment and rehabilitation. The company currently employs 800 people worldwide and in the last year alone (2015–2016), Blatchford achieved a 25% increase in global sales. The company invests 10% of its revenue back into further research and development, which means that it is already working on future advances that could potentially make use of 3D printing to deliver even greater customisation and more patient benefit.

For more information, visit **linx.endolite.co.uk**

DESIGNING AND MANUFACTURING WORLD-CLASS ENGINES

JAGUAR LAND ROVER

Jaguar Land Rover has designed and built from scratch a world-class engine family with the creation of a state-of-the-art manufacturing facility in the UK.

Jaguar Land Rover is the UK's largest automotive manufacturer, with a history going back almost 70 years. The company has been named as a finalist for the 2016 MacRobert Award in recognition of the world-class innovation behind the most significant decision the company has ever made: to design and manufacture its own engines for the first time in a generation.

In 2011, it was announced that Jaguar Land Rover would invest £1.5 billion a year for the next five years in new product development. The design, development and creation of a new family of Ingenium engines supports the company's aim to be completely self-sufficient in the design and manufacture of all engines by 2020. Starting with little more than a blank sheet of paper and an empty field, the Jaguar Land Rover team has developed an entire suite of world-leading Ingenium engines that meet the growing demand for lower fuel consumption and cost of ownership, without compromising vehicle performance and driver experience, and delivering commercial robustness for the company now and into the future. The first diesel Ingenium engine was launched in January 2015, and the petrol engine is due to launch later this year.

The Ingenium assembly line at Jaguar Land Rover's state-of-the-art Engine Manufacturing Centre, near Wolverhampton. The facility was built from scratch to produce the engines © Jaguar Land Rover

INNOVATION

The Ingenium engines are the result of almost 200 innovative ideas, which led to more than 100 new patent applications. These were combined to deliver significant emissions and weight reductions alongside improved performance and fuel economy. A key aspect of this was to deliver the lowest engine friction, using the latest engine system technologies. Despite adding features and increasing power output, Ingenium engines weigh up to 40 kg less than other equivalent engines.

In order to build the Ingenium engines, Jaguar Land Rover built an entire manufacturing facility from scratch, which presented an opportunity to create a world-class manufacturing environment. In 2012, building work started on the £500 million, 98,000 m^2 state-of-the-art Engine Manufacturing Centre (EMC) just outside Wolverhampton, and work is currently underway on an 85,000 m^2 expansion worth in excess of £450 million. The EMC also has impressive green credentials with one of the largest solar panel roofs in the UK, which can generate up to 30% of the site's electricity needs.

BENEFIT TO SOCIETY

Filling a brand new factory with skilled staff presented its own challenge, and Jaguar Land Rover took a new approach to creating job opportunities and upskilling the local community. Every EMC employee undertakes an intensive two-week immersive training programme called the Powertrain Way, which has successfully introduced bus drivers, bricklayers and beauticians to new careers in engineering. Wolverhampton has the second highest unemployment rate in the UK, and the EMC is already providing a large number of opportunities in the region. The facility opened in 2014 and already has almost 1,000 employees, with a further 5,500 in the supply chain. More than 40 people have enrolled on an apprenticeship programme, and last year Jaguar Land Rover opened an Education Business Partnership Centre working with local schools to encourage children to pursue STEM subjects.

For more information, visit **http://bit.ly/1T9FATv**

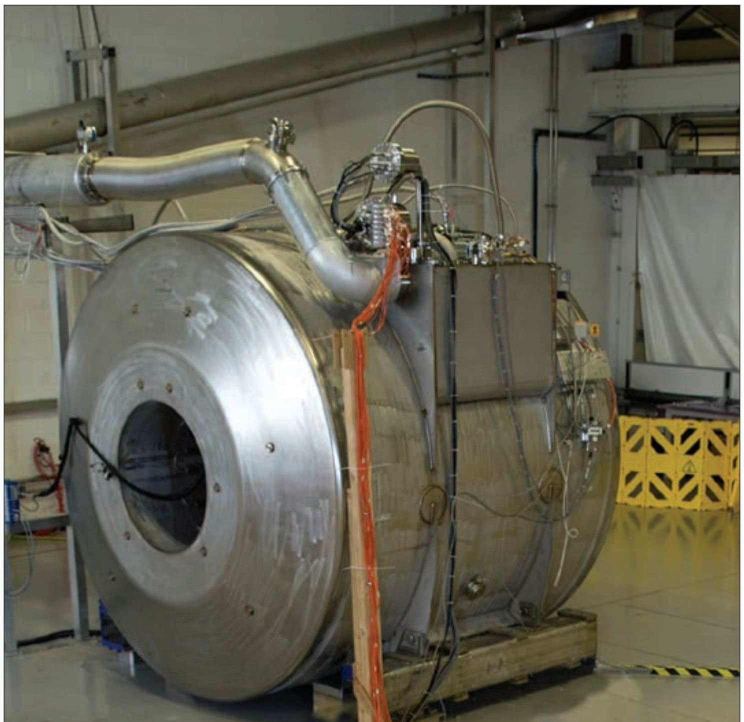
IMPROVING ACCESS TO THE GOLD STANDARD OF MRI SCANNING

SIEMENS MAGNET TECHNOLOGY

Siemens Magnet Technology (SMT), an Oxfordshire-based subsidiary of Siemens Healthcare UK, has developed the first 7 Tesla magnetic resonance imaging (MRI) magnet suitable for clinical applications.

MRI scanners use strong magnetic fields and radio waves to produce detailed images of the inside of the body. They can be used to examine almost any part of the body, and the stronger the magnetic field, the higher the resolution of images that are produced. The first MRI scanners, developed in the 1970s, had a magnetic field strength of well under 1.0 Tesla. Today, most MRI scanners operate at 1.5 to 3.0 Tesla, and have become an invaluable diagnostic tool, used to help millions of patients around the world.

With double the field strength of most MRI scanners, SMT's magnet enables much higher resolution images. The ultra-high magnetic field (UHF) 7 Tesla (7T) system offers sharp enough images to show vascularity of the brain without the pigment that is usually required for contrast. This allows researchers to identify lesions and bleeds, and specific areas of the body affected, more easily, potentially enabling unprecedented insights into hard-to-diagnose conditions.



The 7 Tesla magnet has now been incorporated into the MAGNETOM Terra system, which will offer clinicians and researchers access to the best of MRI imaging © Siemens Magnet Technology

INNOVATION

Achieving such a leap forward in magnetic field was a huge engineering challenge. A MRI magnet is composed of a number of coils of thin wires carrying a high current. The move from 3T to 7T required the addition of enough wire to stretch between London and Brussels. These coils then need to be cooled to 4.2 Kelvin to enable the wire to become superconducting and carry enough current to generate a magnetic field 140,000 times that of the Earth's own. The magnet is vacuum insulated, like a thermos flask, in order to maintain the large temperature gradient between ambient conditions and -269ºC around the inner magnet coils.

SMT's system is half the weight of other current technologies and is pre-assembled and cooled at the factory ready for air freighting, unlike conventional ultra-high field MRI scanners, which have to be shipped in parts and assembled and cooled *in situ*. This saves several weeks and also cuts the helium requirement, a key advantage given the global helium shortage. The 7T magnet has now been incorporated into the MAGNETOM Terra system, which will offer clinicians and researchers access to the best of MRI imaging.

SMT, which employs 420 people at its Oxfordshire site, was able to achieve this remarkable step-change in MRI capability by starting from scratch rather than making incremental improvements to their existing technologies. By investing heavily in R&D, and probing the absolute physical limits of the technology, the team completely re-invented the superconducting magnet, creating a smaller, lighter, better integrated structure.

BENEFIT TO SOCIETY

The MAGNETOM Terra will enable new insights into neuro-degenerative diseases, such as Alzheimer's, Parkinson's and multiple sclerosis, which represent some of the largest unmet challenges within medicine today. It could also assist in drug development through improved pre-screening of clinical trial participants to ensure that their conditions are similar, enabling more efficient drug trials. There is the possibility it could be used to help develop treatments for early-stage diseases and enable monitoring of the efficacy of existing treatments, detecting, for example, whether chemotherapy drugs have penetrated a cancerous tumour.

For more information, visit **http://sie.ag/1UVtUDb**

A WEB OF NETWORKS

Information technology has come a long way since David Cleevely CBE FREng investigated the suitability of computers for word processing and communications. Computers are now so cheap that his latest venture, the Raspberry Pi, was a giveaway on magazine covers. He talks to Michael Kenward OBE about how he has been shaking up innovation in the UK and trying to do something about the advice that governments receive on technical matters.

Dr David Cleevely CBE FREng © Cambridge Ahead

When Cleevely turned up for an interview with the Post Office, he had done enough strange things to persuade them that he might be an interesting candidate

Networks have always been important for David Cleevely CBE FREng. His first job, at what was then Post Office Telecommunications, now BT, was thinking about the future of communications networks. These days, his networks are as much about people as things, and often local to Cambridge, Cleevely's base since he moved there 30 years ago to do a PhD. Cleevely's 'virtual networks' include a band of 'angel' investors who back start-up businesses, often commercialising local research. Then there is the network of movers and shakers that Cleevely is involved in as Founding Director of Cambridge University's Centre for Science and Policy (CSaP), a think tank that "helps the sciences and technology to serve society by promoting engagement between researchers and policy professionals". Another network brings together schools around the world as they write programs to run on the Raspberry Pi computer platform that has been an unexpected hit for Cambridge's network of IT enthusiasts and researchers. Then there are networks of people keen to see that the city gets more than its fair share of communications infrastructure.

AN ENTERPRISING EARLY LIFE

This 'people networking' grew out of Cleevely's early work with the Post Office on telecommunications networks, a role that might never have happened. "That was an accident, like so many things in my life," he says. The Post Office had sent someone to his school to try to coax sixth-formers to consider a career with the then nationalised post and telecommunications business. As Cleevely describes it, he was strolling down a school corridor during a break and went along "to fill up the numbers". He took notice when he heard that the Post Office might give him a grant to go to university.

When he turned up for an interview with the company, he had done enough strange things to persuade them that he might be an interesting candidate. Cleevely had built homemade rockets and there was the school biology field trip where, rather than getting down on his hands and knees to count bugs and flowers, he decided to go up in the world. "I wanted to try and get a complete picture so I built a kite with a camera suspended under it to try and take aerial photographs of the area." Cleevely also started his entrepreneurial activities around then, again with bugs and flowers involved. "I started a beekeeping club at school. I sold the honey to recoup the cost of the hives."

When it came to picking a degree course, Cleevely opted to study cybernetics. The attraction, he explains, is that it "was about control and robotics, artificial intelligence and all that kind of stuff". He went to Reading University, one of the few institutions that taught the subject. In line with his extracurricular goings-on at school, where he was involved in acting, directing school plays and writing music, at university Cleevely got involved in other activities. "I played around a bit in politics. I played around with economics." Both topics came to be increasingly important as Cleevely's career progressed.

Cybernetics may have been a fascinating undergraduate subject, but Cleevely didn't see it as a career option. "I went into the long-range studies division at Post Office Telecommunications." This internal think tank, based in Cambridge, pondered the future of telecommunications. "We were looking ahead 20 or 30 years," Cleevely explains.

The 1970s were interesting times for telecoms. Back then, the telephone network did little more than handle telephone calls, but there were hints of things to come. "I had to look at what might happen if you had a computer on your desk. Could you use it for word processing and messaging as well as for doing computational stuff, and what would the implications of that be?"

One piece of research sticks in Cleevely's memory. Telecoms in the 1970s were entering the digital era, with telephone exchanges abandoning mechanical switches for electronic digital switching. Post Office Telecommunications wanted to assess how the prices of electronic components might develop. By coincidence, Cleevely had just read a book that has since acquired legendary status: Gordon Moore's account

The latest move in David Cleevely's continuing aim to get better telecoms in Cambridge is a new campaign for the rollout of better broadband, wi-fi and mobile services through the Cambridge Ahead network, which launched the #CambsNotspotter initiative to identify gaps in service in the area. He is seen here with representatives from some of the other partner organisations at the initiative's launch event © Cambridge Ahead

of the thinking behind his 'law' showing that the number of transistors that you could cram on a chip would double every 18 months or so. "I did some digging into the fundamental physics of memory devices and some of these other things. I thought about the economies of scale and I just went 'There is no limit to this. We are so far away from the physical limit'."

The views of a young rebel did not go down well. Everyone else in the business had predicted prices falling by around 3–8% a year, and here was Cleevely forecasting falls of "30, 40, 50, 60% a year, and not just for one year. It goes on". His analysis provoked a visit from London and a request to reconsider his forecast. Cleevely demurred and the Post Office removed his analysis from the exercise.

It wasn't all lost causes for the young Cleevely. His boss took him along to University College London to advise on a bid for backing. "This new project was absolutely weird and wacky at the time," Cleevely recalls. "These Americans had this idea of breaking information up into packets and sending them across the Atlantic. They wanted us to join this funny thing called the DARPAnet [the US's military network]." The project was all about protecting the network from a nuclear attack. "Could you extend it via satellite out to the UK and would Post Office Telecommunications collaborate?"

The pitch may have been hard to follow, but the idea appealed to Cleevely, who advised his boss that "someday all information will go by packets". Looking back, he comments: "I don't claim that I had thought that remark through," but adding this idea to his understanding of the likely impact of Moore's law convinced Cleevely that packet switching would do much to smash the cost of communications.

This success did not persuade Cleevely to stick with the Post Office. The rejection of his views on the likely cost of electronics didn't go down well with him and prompted Cleevely's next career move. "It confirmed to me that they did not understand how the world was changing around them. I didn't really want to be a part of that because it was going to be very frustrating."

He left to pursue a PhD at Cambridge on telecommunications and economic development. In part this was, he says, because he wasn't sure that his 'intellectual toolbox' was up to scratch. He wanted to do something about that and embarked on applying what he calls "some old geography theory" to telecommunication.

With his PhD completed, Cleevely put his research to use by joining the Economist Intelligence Unit (EIU), writing reports for clients on the economic aspects of telecoms technologies and applications. For example, one project for BT looked into putting optical fibre into the City of London. Then there was a series of projects for the EU on the economics of telecoms.

Cleevely's role as an 'angel', investing in new businesses, was developing. He was co-founder of a network of Cambridge angels in 2001 when Robert Sansom, another local entrepreneur who had had a number of successes in the USA, asked why there wasn't one

TURNING EXPERIENCE INTO SUCCESS

Cleevely says that he made a lot of mistakes during his two and a half years at the EIU, but that did not stop him from becoming head of the telecommunications division. Telecoms consulting was, after all, a new activity. He learned a lot and built up enough contacts to set up his first business, Analysys, a consultancy that set out to go beyond the work of the EIU. Analysys started up with some work for the EU. "I understood how the European Commission works," he says with a laugh. "It is a strange and wonderful beast."

Analysys arrived at just the right time. The company's business quickly progressed from straightforward consulting into projects modelling telecommunications investment in Europe. This was a big contract that prompted Cleevely to recruit software engineers to write the software for the models and the systems that he believed Analysys would need to survive. "I saw that the future of consultancy was going to be in how well you could manage information and what we would call now process flow."

The modelling work was something of a breakthrough. "We were the only people to be able to model how telecommunications investment was likely to emerge. What the modelling did was to establish our reputation as people who understood the intersection of economics and telecommunications, engineering economics."

By the end of the 1990s, the world was waking up to the importance of telecoms. It was also beginning to see the value of software and the potential of what was to become the World Wide Web. The software that Analysys developed didn't just give the company an edge in its modelling, it played a part in how it handled information internally. "The systems that we were then building meant that we were able to share knowledge and expertise during the 1990s so that when the internet and the web came along we were already pre-adapted."

SOFTWARE EXPERTISE

The software expertise also proved valuable when Cleevely became involved in another of life's unexpected events: the start of a new business that was to change his life. In another of those networking dinners, Cleevely was sitting next to Jonathan Milner, a young researcher looking at breast cancer. Frustrated by the quality of the antibodies he had to buy for his research, Milner wanted to sell high-quality antibodies. Long before shopping on Amazon became commonplace, Milner and Cleevely came up with the idea of a web-based business. "Analysys had all the web-based tools for doing this," Cleevely explains. "We had already developed the technology." In effect, he adds, Analysys "did a tech transfer and built the web systems for them".

Cleevely liked Milner's idea so much that he invested in Abcam, the new company set up in 1998 to commercialise it. Cleevely chaired the business until 2009, by which time he had overseen the public float of Abcam, turning it into a billion-dollar business.

As Cleevely points out, it is somewhat ironic that he made his 'big money' in life sciences rather than telecoms, his original expertise. However, thanks partly to the success of Abcam, Cleevely was also behind a number of telecoms start-ups; 3Way Networks, for example, which produced wireless base stations for domestic and business use, was sold to Airvana. "A lot of the people from that are working with me in other companies at the moment." So that network survives. Then there is his investment in businesses that have nothing to do with technology. His biggest, he says, is in award-winning London restaurant, Bocca di Lupo, along with a Cambridge pub.

Cleevely can't remember how many companies he has backed. "It's about 60 or 70." There have also been a few failures. Again Cleevely is vague on the numbers. "Six, eight things that have gone bust. Maybe 10. I don't know. They have been fairly small," he adds. Apart from the one that got away, that is; a web business called Trutap came to nothing when the hedge fund that was supposed to back it pulled out without warning. Again, Cleevely laughs off the failure, pointing out ruefully that a few months later a lookalike start-up, Whatsapp,

Tony Blair, then prime minister, with David Cleevely at the launch of the *e-commerce@its.best.uk* report in Cambridge in 1999, a cue for some networking to improve the city's telecoms © Cambridge Evening News

opened for business and went on to become another of those billion-dollar Silicon Valley superstars. Five years later, Facebook paid nearly $20 billion for it.

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Cleevely added to his investment pot when he sold Analysys to Datatec International in 2004. "I took some cash away from that. It is not money to be sneezed at." This sale ended his days of full-time employment. "But as my wife explains, I am probably busier now than I have ever been."

INFLUENCING POLICY

Cleevely's busy-ness takes in several major activities that exploit his networking skills. Perhaps the most visible is as founding director of the CSaP, with a remit "dedicated to bringing together the best scientific thinking across all disciplines in order to inform public policy".

Cleevely says, half-jokingly, that he got the job because the university couldn't find anyone else. In reality, Cleevely was a good choice to run the CSaP because he wasn't yet another academic intent on running research programmes and producing papers read by no-one outside the community. He admits that there was pressure to churn out reports that they could deliver to policymakers "to get them to change their policy", as he puts it. That notion is, he insists, "bonkers, absolutely bonkers. It is a self-serving misrepresentation of what is going on in policy formation".

Cleevely talks from experience when he describes how policy happens. As well as his consulting work over many years, he contributed significantly to a report requested by the Prime Minster's Office, *e-commerce@its.best.uk*, "laying the ground for what we had to do to improve e-commerce in the UK". When Tony Blair, then prime minister, launched the report in Cambridge in 1999, Cleevely used the event as a way of using his network of contacts to persuade British Telecom to bump Cambridge up the list of places where it would roll out broadband. To this day he continues to campaign, through a network known as Cambridge Ahead, for better telecoms in the area.

It is this ability to operate 'off piste' that Cleevely is keen to promote at the CSaP. "My logic is that the research is sitting there already," he says. "The focus was not on policy content, it was on organising events. It was all about networking."

Cleevely sees limited benefit in parachuting academics into policy circles. After their time in the corridors of power "they mostly go back to doing their academic work". He believes it is better to work the other way round. "If you put a policymaker into an academic environment for a few days they go back; they have understood where a lot of the research is coming from, a lot of the dynamics and a lot of the networking. If they have got a problem, they have got a ready-made network." The networks are growing: "We have 220 policy fellows, and over 1,000 academics and other experts. More

David Cleevely networks with CSaP policy fellows at one of its Policy Challenge events, held at the Royal Academy of Engineering. CSaP's Policy Challenge initiative aims to identify and address high-priority public policy issues © CSaP

than 6,000 meetings have taken place between them."

He cites a recent example of a meeting for the permanent secretaries and director generals who run government departments and agencies. The event was all about artificial intelligence (AI). The delegates arrived wondering why they were there, but left convinced that AI would be important for their departments. As Cleevely reports it, the response was: "As far as I am concerned the impact of AI on my department is going to be far-reaching, and I'm going back and I'm going to have to take this into account."

ANOTHER PIECE OF THE PI

Another important venture that Cleevely has got involved in, the Raspberry Pi, depends on a different local network. He describes this credit-card-sized computer as his current engineering passion. Indeed, you could say that it has reawakened his interest in engineering. Raspberry Pi is a single-board computer designed to introduce youngsters to programming or coding. For as little as five dollars, you can buy a basic computer. "It is the only computer that has ever been given away for free on the cover of a magazine," says Cleevely with a characteristic laugh. The latest incarnation of the device, the Pi 3, is potentially a desktop computer at $35, says Cleevely. Made at Sony's factory in South Wales, "it is a huge British success story".

There are two arms to the Raspberry Pi operation: a trading company makes and sells the hardware and the Raspberry Pi Foundation uses the profits to support educational activities around the world. Raspberry Pi first asked Cleevely to join the board of the trading company as he knows "a bit about this stuff". It was then decided that he would be a good candidate to chair the foundation.

Cleevely has even found ways of tapping the Raspberry Pi in his business activities. "Several of the companies that I am chairman of are using the Raspberry Pi for industrial applications." OpenIOLabs, for example, started with the aim of selling microscopes. "To make it work you need a controller to drive the microscope." After a slow start selling microscopes, OpenIOLabs changed direction and started making controllers that could handle all manner of devices and systems. "Every single gadget that you are now connecting up, you just have one universal box that connects everything and allows you to control and collect data." The company has already sold systems to CERN, the Lawrence Livermore National Laboratory in the USA, and the local plant biology labs.

The Raspberry Pi was the brainchild of researchers at the University of Cambridge's Computer Laboratory, who were concerned about the decline in the numbers and skills levels of the A-level students applying to read computer science. They turned to ARM, another part of the local Cambridge IT networks, and used Broadcom's processor based on ARM technology to design a credit-card-sized computer. The company has already sold more than eight million of them

Once again, Cleevely's overlapping networks mean that business, engineering and social activities rub shoulders. The latest addition to Cleevely's web of networks, called the School for Scale Ups, will help companies to survive growing pains as they move from being a start-up to a profitable business. "As entrepreneurs, starting a company and having a business idea, that is just the beginning," says Cleevely. "You need to understand how to grow it."

This one comes under the umbrella of the Cambridge Network, a new member of the web of networks that Cleevely helped to spin, and one that acts as an umbrella for many local initiatives. With 1,500 members, the Cambridge Network is, he says, "everybody in high tech and the University of Cambridge networking together". Cleevely may be sitting in the middle of a bewildering array of networks, but he is still aware that you have to be careful in how you use all those contacts. "Networks are good except when they are subverted for purposes that might be non-transparent and against the public interest. In which case they become the Mafia." So far, he seems to have avoided that in Cambridge.

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, **1953**. Post Office student, **1972–1976**. Awarded BSc in cybernetics and instrument physics with mathematics, University of Reading, **1976**. Awarded PhD in telecommunications and economic development, University of Cambridge, **1982**. Director of telecoms division, Economist Intelligence Unit, **1982–1985**. Managing Director then Chairman, Analysys Ltd, **1985–2004**. Chairman and Founder, Abcam, **1998–2009**. Co-founder, Cambridge Angels, **2001–present**. Fellow of the Institution of Engineering and Technology, **2003**. Chairman and Co-founder, 3WayNetworks, **2004–2007**. Chairman and Co-founder, CRFS, **2007–present**. Chairman of the Advisory Council and Founding Director, Centre for Science and Policy, University of Cambridge, **2008–present**. Fellow of the Royal Academy of Engineering, **2008**. Chairman, Raspberry Pi (Trading) Ltd., **2012–present**. Fellow Commoner, Queens' College, University of Cambridge, **2013**. Commander of the Order of the British Empire, **2013**. Chairman of the Board of Trustees, Raspberry Pi Foundation, **2014–present**. Honorary Fellow, Trinity Hall, University of Cambridge, **2015**.

INNOVATION WATCH

THE QUICK FIX DIY SOLUTION

Launched on Kickstarter in November 2015, British designer Peter Marigold's FORMcard innovation successfully raised the money needed to go into production on its first day. The malleable plastic has since been used to fix thousands of everyday items around the world.

FORMcard is small enough to fit in a wallet. Once heated, it becomes sticky and pliable, allowing it to be moulded into various shapes before hardening © FORMcard

FORMcard is a colourful credit-card-sized piece of bioplastic that melts in boiling water and can then be moulded when hot and pliable to fix a number of items, from screwdrivers and toys, to car wing mirrors and bumpers.

Designer Peter Marigold has worked on gallery displays, installations and public art projects. After becoming interested in plastics that melt at low temperatures and looking at how they could be adapted to be used in the home, he developed the idea for FORMcard.

The cards are produced entirely in the UK and are made from a high-molecular-weight thermoplastic linear polyester derived from a bioplastic monomer. The thermoplastic is non-toxic and uses powder pigments instead of universal pigments containing styrenes, which can be hazardous to humans. These types of thermoplastics are usually supplied as granules, which have to be squashed together before using and result in a bulky piece of plastic. It isn't convenient for people to carry round bags of the granules with them, so FORMcard aims to be easier to use and more accessible so that people can make their repairs wherever they are.

When it is very hot, the plastic becomes sticky and can stick to other plastics, such as ABS (acrylonitrile butadiene styrene), polyester, vinyl and acrylic, allowing it to fix and modify items. Once the plastic cools down slightly, it loses its stickiness but can still be moulded into various shapes before hardening, such as mobile phone stands or wall hooks that can hold up to 10 kg. It can be reheated and, once it has served its purpose, melted again and used to fix something else.

The reusability and accessibility of FORMcard aims to provide people with a simple fix for their items rather than them having to be thrown away, so it is an eco-friendly and sustainable solution. Since it went on sale in December 2015, more than 60,000 FORMcards have been sold and agreements have been made with distributors in New Zealand, Australia, South Africa and the USA.

For more information, see **formcard.co**

HOW DOES THAT WORK?

LI-FI

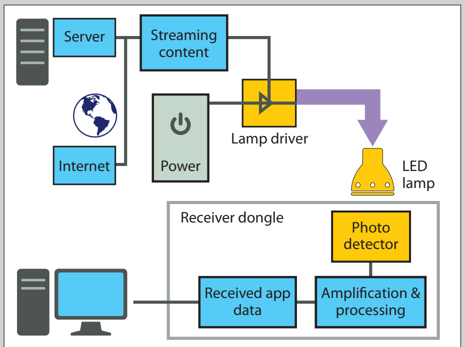
Light fidelity, or 'Li-Fi' as coined by inventor Professor Harald Haas, is a wireless communications technology that transmits high-speed data via common household light emitting diodes (LEDs).

As LEDs are semi-conductor light sources, the current of electricity can be brightened and dimmed at ultra-high speeds. Therefore they can be switched on and off faster than the naked eye can detect, making the light source appear to be on continuously. While to us these changes in amplitude go unnoticed, they can in fact enable the transmission of data at rapid speeds.

Data is fed into an LED lightbulb embedded with a microchip with signal processing technology. When the data is streamed, the changes in amplitude causing the LED to turn on and off allow the data to be transmitted in binary code. A photodiode detects the light stream and transforms the amplitude fluctuations into an electric current.

The electrical signals are then converted back into a data stream and transmitted to a computer or mobile device, where a binary data stream runs web, video and audio applications.

Li-Fi has almost no limitations on capacity as the visible light spectrum is 10,000 times larger than the entire radio frequency spectrum used by Wi-Fi. Li-Fi is also less susceptible to interference, as visible light cannot pass through walls.



Data is streamed via an LED lamp with signal-processing technology