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JUNE 2017 ISSUE 71

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An image of Prospero from the Royal Shakespeare Company's latest production of *The Tempest*, which uses motion-capture technology live on stage © Royal Shakespeare Company

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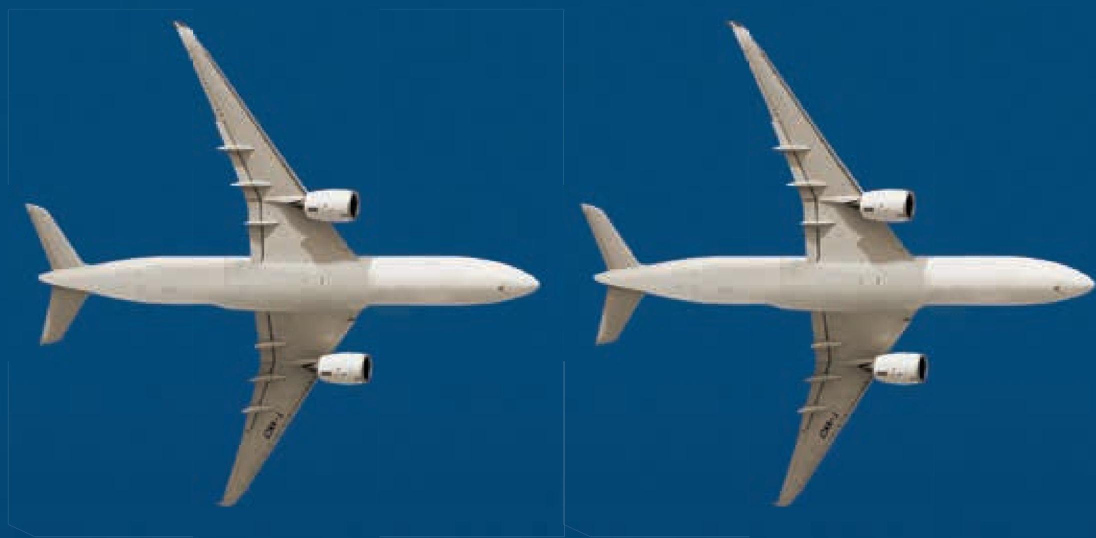

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EDITORIAL

ENGINEERS MAKE THINGS BETTER

Dr Scott Steedman

'There is no doubt in my mind that our future prosperity and comfort depends on the talents and ingenuity of engineers', wrote the Royal Academy of Engineering's Senior Fellow, HRH The Prince Philip Duke of Edinburgh KG KT OM GBE, in May 2006. Later this year, His Royal Highness will step down from public duties (although not from the role of Senior Fellow), four decades after the launch of the Fellowship of Engineering, which later became the Royal Academy of Engineering, at Buckingham Palace on 11 June 1976.

In the early 1970s, Prince Philip was instrumental in the success of negotiations over the establishment of a new body that could become a home for engineering, a new national academy working alongside the Royal Society. He told that story in an article for *Ingenia*, published in 2009 ('Promoting engineering', *Ingenia* 41). In his own words, he described his interest in engineering at many levels, from his experiences as a young naval officer to his continuing role as the Academy's Senior Fellow. Three aspects stand out for me that will resonate with many in the profession.

Firstly, making things better! In the article, he explains how his interest in all things technical was sparked while he was a midshipman in the Royal Navy in 1939, sketching engineering components and relating how they worked to how they looked. Since then, his deep curiosity and keen interest in engineering has never wavered.

In 1959, he launched the Prince Philip Designers Prize, which he chaired and which was overseen by the Design Council for 52 years. Over that time, the annual prize became a celebration not only of the great but the unknown designers behind everyday objects, creative experts in disciplines ranging from technology, engineering and architecture to graphics, illustration and fabric design.

Skills start young and Prince Philip's interest in the education and training of engineers has been a constant source of inspiration for many in the profession. In 2005, Chris Wise FREng and Ed McCann wrote an article for *Ingenia* ('Building to learn', *Ingenia* 24) that featured a 'constructionarium' in Norfolk, where students could learn through building large mock-ups of real projects. Within months, he visited the site to see what it was all about.

Beyond professional qualification comes public recognition. Prince Philip is credited with the creation of the Academy in the 1970s, driven by his own vision and personal interventions. Indeed, in an era when engineering was seen as secondary to science, 'Prince Philip saved engineering in the UK', as Lord Browne FREng FRS said in his interview with him on BBC Radio 4's *Today* programme in January 2016. What followed, through the work of the Fellowship of Engineering and subsequently the Academy, was to change the public face of the profession completely. Today, in a testament to that early vision, the Academy is working with the professional engineering institutions (PEIs) and leading the debate on the role and contribution of engineers and engineering in society, innovation and the economy.

Above all, it is Prince Philip's enduring interest in people working as engineers that stands out in his writing. Since 1989, the Prince Philip Medal has been 'awarded periodically to an engineer of any nationality who has made an exceptional contribution to engineering as a whole through practice, management or education'. But he has also been a champion of broadening access to engineering to those without a formal academic education. His encouragement to promote routes for apprentices, technicians or others without university degrees to become engineers was echoed in the recent report by Professor John Uff CBE QC FREng, *UK Engineering 2016*, which called for more coordination and flexibility across the PEIs as an important mechanism to attract more young people into engineering.

The challenge of attracting talent into the profession is not new, but has never been more urgent. From cities and infrastructure to the digital economy, healthcare and emerging technologies, there is widespread recognition that not enough young people are becoming engineers. Just as Prince Philip proposed in the 1970s, this is surely the moment for all in the profession to rally round a common voice and a single message. Let's start by saying thank you.

Dr Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

LEARNING TO BE AN ENGINEER

Primary school students take part in a workshop that is designed to encourage 'engineering habits of mind'

Reframing engineering as a set of habits of mind is a helpful and practical way of raising students' achievement across all subjects, according to the findings of a report carried out by the Royal Academy of Engineering and the University of Winchester's Centre for Real-World Learning.

Research for the *Learning to be an Engineer* report found that schools that adapted their teaching to encourage students to develop 'engineering habits of mind', such as learning from failure and playful experimentation, saw benefits not just in science and maths, but in pupils' communication skills, creative problem-solving and confidence to engage in class discussions.

The report uses the results of three pilot schemes that worked with teachers in southern England, Greater Manchester, and Glasgow and East Ayrshire, describing ways in which a curriculum based on the 'engineering habits of mind' boosted pupils' achievement and enhanced teachers' confidence to engage with the engineering profession. The pilot scheme involved 22 primary schools, 11 secondary schools and one further education college, with 84 teachers and more than 3,000 pupils taking part.

Professor Bill Lucas, Director of the Centre for Real-World Learning at the University of Winchester, said: "If we are going to attract more young people into engineering, schools have to rethink the way they teach. The *Learning to be an Engineer* research has shown that, if you choose learning methods that foster engineering habits of mind such as problem finding and solving, systems thinking and visualising, then learners become more engaged."

REPORT PUTS FORWARD 5G PLANS

In March, the government set out a strategy, *Next Generation Mobile Technologies: A 5G strategy for the UK*, outlining its ambition for the UK to become a global leader in 5G, and create a world-leading digital economy.

There are three main outcomes that the government hopes to achieve: accelerating the deployment of 5G networks; maximising the productivity and efficiency benefits to the UK from 5G; and creating new opportunities for UK businesses at home and abroad, while encouraging inward investment.

The government hopes to meet the aims by creating a new national 5G Innovation Network that will trial and demonstrate 5G applications. This will be funded by a £16 million investment in a cutting-edge facility. The government will also be establishing a new centre of 5G expertise in the Department for Culture, Media and Sport to ensure that work to develop 5G capabilities across the UK is unified.

A good digital infrastructure is an important part of any future industrial strategy; sectors across the whole of the economy are expected to make use of new 5G technologies and applications, including transport sectors financial services and retail.

In the foreword of the report Karen Bradley MP, Secretary of State for Culture, Media and Sport, and Baroness Neville-Rolfe DBE CMG, Commercial Secretary to the Treasury, explain: "We want to enjoy the benefits of new 5G networks early on: faster, more reliable connections; new, valuable services from connected cars to smart factories; and more high-paid, high-skilled jobs."

To read the report in full, please visit **www.gov.uk/government/publications/next-generation-mobile-technologies-a-5g-strategy-for-the-uk**

ENTERPRISE FELLOWSHIPS AWARDED

The Royal Academy of Engineering's Enterprise Hub has awarded Enterprise Fellowships to 12 UK researchers to help them turn their innovations into successful products and companies.

The Fellowships provide funding of up to £60,000 each and aim to help researchers get new technologies to market. As members of the Enterprise Hub, the Enterprise Fellows will be provided with a package of support that includes training and networking events, access to the Academy's new Taylor Centre – a dedicated home for the Hub with state-of-the-art meeting and networking facilities – and business mentoring from an Academy Fellow.

The new cohort of Enterprise Fellows includes Dr Felicity de Cogan, founder of NitroPep and inventor of a coating for steel that kills bacteria on contact. The NitroPep technology uses a surface modification process that imparts nanosized 'spikes' that insert into the bacteria and pop the cells. Developed for use in hospitals, the technology will reduce bacteria on surfaces and prevent cross contamination between patients, helping to prevent hospital-acquired infections.

Another new Enterprise Fellow, Dr Enass Abo-Hamed, CEO at H_2GO Power, invented a clean, efficient and affordable hydrogen-storage solution made from innovative smart nanomaterials. She hopes that the battery will help some of the 1.2 billion people in the developing world who do not have access to a reliable power supply for cooking, lighting, studying or medical treatment.

The 2017 Enterprise Fellows are the fourth cohort of engineers to receive support from the Enterprise Hub since it was established in 2013, following in the footsteps of alumni who, between them, have established 45 startup companies, generated 150 jobs and raised over £30 million in follow-on funding.

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

The 12 inventors who were awarded Enterprise Fellowships in 2017

UK ROBOTICS WEEK RETURNS

UK Robotics Week is returning for a second year between 24 and 30 June 2017 to showcase leading UK technology in robotics and autonomous systems. It will offer activities for people of all ages across the country, including open days and lectures, film premieres, competitions, cutting-edge robotics demonstrations and exhibitions.

This year's Robotics Week is focused on five central challenges that aim at promoting creative solutions, inspiring tomorrow's technologists, and pushing the boundaries of robotics and autonomous systems innovation.

Events include the premiere of *Extreme Environments Challenge 2017*, a film that demonstrates how robotics and autonomous systems can be used in emergency and disaster response. The Surgical Robot Challenge 2017 will showcase live demonstrations of surgical innovations from around the world. Another two-day event focuses on infrastructure, by bringing together academics, industry, policymakers and stakeholders to explore future use of both air and ground robots in the creation, inspection, repair and maintenance of critical infrastructure. There will also be a demonstration of a Pepper robot to show the latest developments in social care technologies.

The week will also feature a School Robot Challenge 2017, a competition aimed at inspiring schoolchildren through computer-aided and bio-inspired design.

As part of Robotics Week, the Royal Academy of Engineering will be hosting an *Innovation in Haptics* event to showcase a selection of the most recent advances in haptic technologies and virtual reality across all sectors. The half-day event will feature talks on how new haptic interfaces are being used to replicate real-world environments, within which new autonomous vehicle concepts can be tested, and how haptic devices are being used to help build synthetic viewing systems and simulations of complex operations involving robots."

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 Science Museum, RACE, Royal Academy of Engineering, the Institution of Engineering and Technology, and the Institution of Mechanical Engineers.

For more information on UK Robotics Week, please visit **www.roboticsweek.uk**

One of the robots to be showcased at Robotics Week is MiRo, a fully programmeable autonomous platform that is suited to developing companion robot animals © UK-RAS

INTERNATIONAL WOMEN IN ENGINEERING DAY

Attendees at a previous event held as part of National Women in Engineering Day © WES

On 23 June 2017, the first International Women in Engineering Day (INWED) will be celebrated. Established by the Women's Engineering Society (WES) and replacing National Women in Engineering Day, INWED aims to raise the profile and celebrate the achievements of women in engineering across the world, and encourage girls and women to pursue careers in the field.

Employers, schools and colleges, engineers and professional engineering institutions are being encouraged to hold events, such as opening engineering workplaces for student careers visits, asking women engineers to give talks in schools or organising networking events.

The Royal Academy of Engineering is marking the day with a short film that profiles five women engineers under 35 from Mozambique, Uganda, Palestine, Germany and the UK. All of the role models featured in the film have been actively involved in the Academy's activities and have followed varied routes into their careers in STEM. Focusing on the INWED theme of 'men as allies', the film will also highlight the important role that both women and men can play to help improve diversity in engineering.

More information about INWED and resource packs can be found at **www.inwed.org.uk**. The film is available to view from 23 June at **www.raeng.org.uk**

INGENIOUS PUBLIC ENGAGEMENT AWARDS

The Royal Academy of Engineering has announced 17 projects that have been awarded funding under its *Ingenious* public engagement programme, including hands-on workshops, connecting engineers and teachers, and stage shows.

The latest round of projects are set to take place across the UK and will provide new opportunities for members of the public to meet professional engineers and learn about the exciting, creative work they undertake.

Participants take part in a 2016 *Ingenious* project that gave them the chance to work with engineers in the process of designing and building an electro-acoustic guitar, amplifier and speaker system

Projects include graduate engineers establishing a 'young inventors' club' based at the Museum of the History of Science in Oxford, which houses a collection of everyday technology including clocks, cameras and calculators. Another project that works with young people is the 'sludgy stuff' engineering roadshow, which will take a team of researchers into schools and festivals to explore the world of sludge – materials such as custard, paints, magma and cement that present unique engineering challenges because of their unpredictable behaviour – with hands-on activities.

Ingenious projects for adults include a free two-day event for Kent residents to learn more about the world's largest offshore wind farm, allowing local people to work alongside windfarm technicians and engineers to design their own turbines while learning about the technology and associated career opportunities.

The *Ingenious* awards scheme aims to inspire creative public engagement with engineering. The scheme is supported by the Department for Business, Energy and Industrial Strategy, and has funded over 189 projects to date, providing opportunities for over 5,000 engineers to take part in public engagement activities that have reached over 2.5 million members of the public.

RESPONSE TO INDUSTRIAL STRATEGY

A profession-wide collaboration, led by the Royal Academy of Engineering, has produced a response to a recent Green Paper on industrial strategy.

The report emphasises that long-term collaboration and UK industry, academia, government and investors working together as a system to achieve sustainable growth are important factors in the success of the industrial strategy.

The report, *Engineering an economy that works for all*, calls for the strategy to focus on a long-term vision that harnesses the UK's international reputation for engineering excellence and forges a new global identity for Britain as a top destination for inward investment and global talent. It calls for the government to set a target of 3% of GDP combined public and private R&D investment, and to maintain the current level of infrastructure funding after the UK leaves the EU.

The report also asks that government broadens the strategy to encompass developing skills, as well as addressing the shortage of teachers in STEM subjects in both primary and secondary schools. It recommends a focus on promoting STEM subjects and engineering careers to under-represented groups to fully unlock the talent potential in the UK.

Professor Dame Ann Dowling OM DBE FREng FRS, President of the Royal Academy of Engineering, says: "A good industrial strategy will not make government intervention more likely, but it will make it more predictable – and that builds confidence and encourages business investment. The strategy must be long term and sustained, with cross-party and whole government support."

The main points in the report were sent to the manifesto teams of the main political parties.

To read the report in full, please visit **www.raeng.org.uk/industrialstrategy**

HOW I GOT HERE

Q&A

DR SABESAN SITHAMPARANATHAN
ELECTRONIC ENGINEER

Dr Sabesan Sithamparanathan is Co-founder and CEO of PervasID. His company provides radio-frequency identification (RFID) readers for low-cost, long-distance sensing of passive RFID tags, for use in tracking in retail, security and healthcare.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

Between 2001 and 2003, I studied A levels in physics, maths and chemistry in Sri Lanka. I had always been fascinated by, and enjoyed, physics and maths – I think it's important to love your chosen subject and be good at it. While studying, I covered everything from mechanics to electronics, which interested me most as it is so relevant today. Our world is all about technology.

HOW DID YOU GET TO WHERE YOU ARE NOW?

I studied for a BEng (Hons) in electronic engineering at the University of Sheffield. While there, I was awarded the Sir William Siemens Medal for being among the UK's top 18 science and technology students. After I graduated, I worked at ARM as a student electronic engineer, before beginning a PhD in RFID at the University of Cambridge in 2007. In 2011, I was elected to a Research Fellowship at Girton College, Cambridge. In 2014, I was awarded funding and received money-can't-buy mentoring as part of the Royal Academy of Engineering's Enterprise Fellowships scheme to help turn the technology into a viable business.

WHAT GAVE YOU THE IDEA FOR PERVASID?

PervasID is the commercial realisation of my PhD thesis. I chose RFID for my thesis because of the strong level of industry interest in the technology at the time, which the market had failed to satisfy. Since I am at heart an entrepreneur, it presented a commercial opportunity. My goal was to develop a passive ultra-high-frequency (UHF) RFID reader that could offer low cost and reliable reading of standard, off-the-shelf passive UHF RFID tags. In the real world, there are lots of dead spots where radio coverage is poor due to reflection. As a result, the reader does not detect the tags in every location, making the value of the technology limited. Addressing this problem required a fundamentally different approach. PervasID eliminates dead spots by using a distributed antenna system (DAS) network, as well as advanced signal-

RADIO-FREQUENCY IDENTIFICATION

Radio-frequency identification (RFID) systems use electromagnetic fields to automatically identify and wirelessly track tags. RFID tags contain electronically stored information and can be linked up as components of intelligent networks. The sensors can be interrogated via the internet, and their location can be determined from a distance. Passive RFID tags harvest their energy from the radio waves interrogating them and require no internal energy source or maintenance. Active tags have a local power source such as a battery.

processing techniques. The technology achieves nearly 100% detection over areas of up to 400 square metres using a single reader.

WHERE IS THE COMPANY AT NOW?

Following successful trials, PervasID was established in 2011. The technology is being effectively used in retail. One major blue-chip retailer has installed PervasID's readers within a 45,000-square-foot area that covers the goods receiving area, storage, sales and fitting-room areas, with more than 100,000 tagged items. The success of the initial trial helped to release the first seed round of finance in September 2016. At the beginning of May 2017, we launched a second-generation product, the Space Ranger 9200, which delivers the world's first near-100% accurate, wide-area passive RFID detection in real time. This allows retailers, hospitals and other industries to see the stock that they have in a store or building in real time.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

I have always wanted to be an entrepreneur, so creating a University of Cambridge spin-out company is a big achievement. I have also received recognition for my work in engineering. In 2016, I won the Royal Academy of Engineering's Sir George Macfarlane medal, for demonstrating excellence in the early stages of my career; and the Enterprise Fellowship from the Academy has given me valuable mentoring from Professor Andy Hopper CBE FREng FRS, a leading figure in computing.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

I love being an entrepreneur. It is a slightly different skill set to a conventional engineer, but it has been great to become a leader and take my technology from the lab to the real world. It is something that we need to see more and more of from young engineers.

Retailers have successfully used Dr Sithamparanathan's PervasID technology for real-time tracking of stock

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

As the CEO, my responsibilities include overall company management and administration, day-to-day operation, commercial development, technical development, product development, IP strategy and funding. I lead the in-house team and manage suppliers and customers. Last week, we announced our latest product and now our focus is on how to deliver this.

HOW WOULD YOU ENCOURAGE OTHER YOUNG ENGINEERS TO DEVELOP THEIR OWN TECHNOLOGIES?

The best ideas are often the simplest – people often realise how obvious your idea was once you have thought of it! Think in different ways to others, and be prepared for an idea to come to you at any time. As an early engineer, you have all the facilities to think harder, bigger and outside the box, giving you a chance to change the world.

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

Firstly, I would advise everyone to think about their unique skills: what are you good at and what do you love doing? If the answer to that is engineering, then pursue it. If you love what you do and are successful at it, then you will be recognised for your work.

WHAT'S NEXT FOR YOU?

The last few years have seen a dramatic change in the use of low-cost passive RFID tags. Large-scale retail companies now place RFID tags inside their price tags. PervasID has patented RFID technology and has carried out major trials, achieving greater than 99% detection accuracy over a wide area in real time. My aim, as CEO and founder, is to meet all the major customer requirements in the field of retail, security and logistics. Our vision for PervasID is to be a leader in low-cost accurate wireless tracking and sensing.

QUICK-FIRE FACTS

Age: **32**

Qualifications: **PhD in engineering**

Biggest inspiration: **Steve Jobs**

Three words that describe you: **ambitious, conscientious, dynamic**

LETTERS

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

IN SUPPORT OF TIDAL LAGOONS

The news that the government-commissioned Hendry Review supported plans for a tidal lagoon to be built in Swansea Bay ('Review backs plans for tidal lagoons', *Ingenia* 70) is welcome.

Indeed, tidal energy is abundant around the UK and developing projects on our doorstep will foster an indigenous industry and substantial local economic growth, among other benefits. It would be short-sighted if the UK government was not supporting (or subsidising) this new technology now or in the immediate future. What is not to like about clean, renewable and, in the long term, cheap energy at our doorstep?

It has been reported that the government is hesitant to begin work on the potential pathfinder project in Swansea Bay. This could be due to the potential cost of the Swansea Bay Tidal Lagoon project, mainly the capital expenditure costs (CAPEX) of an estimated £1.3 billion. At first sight, this appears expensive for only 500 MW (megawatts). However, a tidal lagoon will have a lifetime greater than 100 years, and hence at some point in the future, the Swansea Bay Tidal Lagoon will produce energy at almost no cost as the capex will be amortised. But as the Hendry Review points out this 'expensive now and cheap (much) later' concept is not easy to sell.

So why is the Swansea Bay Tidal Lagoon CAPEX so high and what are the main challenges for it and other tidal lagoon projects?

First of all, the Swansea Bay Tidal Lagoon is quite small but with a long U-shaped seawall, which is probably the most expensive component of the project. More water can be stored and used for power generation in a larger enclosed area and ideally a tidal lagoon should make use of a curved coastline or a natural bay, so Swansea Bay Tidal Lagoon's U-shape is not ideal. The lagoon's rated capacity of 500 MW is reasonably large, but a tidal power plant does not operate 24/7. There will be holding periods to create the necessary pressure so that the amount of energy generated over the year will be 30% to 40% less than that of a traditional hydropower plant with the same rated capacity that operates at almost 24 hours a day, 365 days a year.

Secondly, and this applies to all tidal lagoons, the generation head is relatively small, typically around two to three metres. Tidal lagoons are 'very-low-head-very-high-discharge' hydropower plants that require big, large diameter and expensive turbines to be able to move vast amounts of water in and out of the lagoon within short periods of time. In comparison, the diameter of a 500 MW low-head (20 metres) traditional hydropower turbine is approximately five times smaller than the tidal lagoon equivalent.

Thirdly, and again all tidal lagoons will face this challenge, a traditional hydropower turbine will operate at peak efficiency almost all of the time because input parameters such as head and discharge will remain constant and the direction of flow does not change. Meanwhile, a tidal turbine will have to 'deal with' a variable water depth for some periods of the time (as the lagoon fills or drains), ambient currents around the turbine diffuser and, even more challenging, a reversal in flow direction approximately every six hours. For the reverse flow, turbine efficiency may not be as high as for a turbine that is optimised for unidirectional flow.

Despite the economic and technical challenges that tidal lagoons face today, their power generation could be an opportunity for the UK to harness its own, clean, renewable, safe and predictable energy. This sustainable industry could create thousands of jobs and secure (part of) the energy for future generations, as well as serving at the forefront of innovation and technology development. The Swansea Bay Tidal Lagoon could potentially become the world-leading example that the industry needs.

Professor Thorsten Stoesser
Director
Hydro-environmental Research Centre
Cardiff University

VIRTUAL AND MIXED REALITY IS TRANSFORMING CONSTRUCTION

The article on virtual reality (VR) in engineering is very timely ('How virtual reality is changing engineering', *Ingenia* 70). New technologies are transforming infrastructure and construction, and VR has a crucial role to play in conjunction with the latest innovations in sensor technologies. It is already being used for the modelling of buildings, as described in the article, but closely related mixed-reality technology can also be used to transform control of the construction process for many other types of infrastructure. This is part of the mission of the Centre for Smart Infrastructure and Construction (CSIC) at the University of Cambridge: to transform the future of infrastructure through smarter information, enabling step changes in construction practice.

CSIC collaborators working with the Construction Information Technology Laboratory at Cambridge, under the direction of Dr Ioannis Brilakis, are working with California-based company Trimble, which provides technology for the construction, geospatial and transportation industries, and with Microsoft to develop an automated inspection process for construction progress monitoring. The Automated Progress Monitoring Inspection App uses Microsoft HoloLens and multiplatform game engine Unity to create a semi-automatic inspection method that aligns the 3D as-planned model to the real world as-built environment. This app allows inspectors to bring the design model out of the office and onto the construction site. It marks the first time a 3D model of a building, a bridge or any other type of infrastructure has been taken off the screen and put onto the real structure as it is being constructed.

The HoloLens allows the wearer to walk through the construction site and automatically see what is on schedule and what is behind schedule. This advance in automation allows engineers to visualise the building information model in full scale at their offices or superimposed on the real structure at the construction site. After automatically placing the 3D model to the correct height and orientation, the user manually adjusts the model by moving it horizontally to fit the actual structure. Once the registration of the model to the real world is secured, an analysis to compare the current as-built status with the as-planned 3D model can be completed. A time attribute is added to every element and the comparison can be performed, enabling status progress to be accurately determined and recorded. This information can be used to monitor and control actual progress, improving productivity by making time- and cost-saving interventions where required.

Construction processes and completed infrastructure can be potentially transformed as this mixed-reality technology is combined with other new tools and technologies, including fibre-optic strain measurement, ultra-low power sensors, vibration energy harvesting devices, photogrammetric monitoring systems, computer vision and data management tools. Used in combination, these new technologies offer a whole-life approach to infrastructure; from design to improved and more productive construction, through to operation, maintenance and eventual decommissioning. Many of these innovations have already been tested and proved on some of the largest civil engineering projects in the UK, including Crossrail, National Grid London Power Tunnels, London Underground station upgrades, and the Staffordshire Alliance West Coast Mainline railway bridges for Network Rail. The opportunity for combining these innovations with mixed-reality technology is exciting.

As Dr Scott Steedman noted in his editorial in the same issue ('A strategy for a digital future', *Ingenia* 70), the digital revolution has opened the door for smarter infrastructure. To enable this, the need to invest in digital infrastructure across the UK cannot be overemphasised. The *Building our Industrial Strategy* Green Paper recognises this and highlights the importance of digital skills, where a large gap appears between the requirements of the future and the level of provision in our education system. Enhancing digital skills at all levels will be key to a successful long-term industrial strategy. STEM subjects should be given much more emphasis in primary as well as secondary schools. To exploit innovative sensor and virtual reality technologies, our future engineers will need to be fully conversant with software, computing and coding; only then we will see the huge potential for smart infrastructure and construction fully realised.

Professor Lord Robert Mair CBE FREng FRS
Centre for Smart Infrastructure and Construction
University of Cambridge

OPINION

ROBOTICS AND AI – DRIVING THE UK'S INDUSTRIAL STRATEGY

Robotics and artificial intelligence have the potential to transform the UK's industry, economy and workplaces. Professor Guang-Zhong Yang CBE FREng, Director and Co-founder of The Hamlyn Centre for Robotic Surgery at Imperial College London and Chair of the UK-RAS Network, sets out how investment in these areas could improve innovation in the UK and secure our place as a world leader in the technologies.


Professor Guang-Zhong Yang CBE FREng

As the UK strives to overcome challenges when competing, not just with low-wage economies but also highly automated ones, we need to be open and fully prepared for changes in the workforce and a shift in the skills base. Repetitive and hazardous jobs will inevitably be at most risk, and highly skilled jobs will be in greater demand along with those that cannot be easily automated. The impact of robotics and artificial intelligence (AI) will affect manufacturing, transport and healthcare, as well as low-skilled jobs in the areas of agrifood, logistics, security, retail, and construction. It is important therefore to assess the economic impact and understand the social, legal and ethical issues surrounding robotics and AI in order to maximise the benefits of these technologies while mitigating potential adverse effects.

For the second year, UK Robotics Week, coordinated by the Engineering and Physical Sciences Research Council's UK-RAS (Robotics and Autonomous Systems) Network and supported by the Science Museum, RACE, Royal Academy of Engineering, the Institution of Engineering and Technology, and the Institution of Mechanical Engineers, provides a spotlight on the UK's technology leadership in robotics and AI by engaging the nation's schools, colleges and universities to develop the digital skills needed to drive the UK's future economy. Communities behind the network are also working closely with government to drive world-leading research in the area and create a vibrant ecosystem that will support British industry and its international competitiveness in this critical time for the country, both politically and economically.

The recent announcement of an industrial strategy for the UK, against the backdrop of Brexit and global political turmoil fuelled by regional conflict and humanitarian crises, is a much-needed boost to our research, innovation and industrial base. It brings some certainty in this uncertain time, demonstrating the UK's drive to kick-start disruptive technologies that could transform our economy, with a clear vision for positioning the UK in the international landscape.

The timing could not have come at a better time. Across the EU and from the USA to China, major industrial

Transport is another area that presents challenges and opportunities for robotics and AI. As schemes to pilot driverless cars mature, automated transportation systems and solutions are set to expand from constrained environments such as airports to public transport, urban centres and other general-purpose environments

nations have identified robotics and AI as strategic economic and policy priorities. Unfortunately, the UK trails behind Japan, Germany, the USA and many other nations in the uptake of industrial robots. This is in stark contrast to the strength of the UK's automotive and aerospace industries.

The Spring Budget confirmed an initial investment of £270 million from 2017 to 2018. Recognising the excellence in research and innovation that exists across the UK, there will be a further investment of £4.7 billion by 2020 to 2021. For the first time, government has singled out robotics and AI in its blueprint for a 'modern' industrial strategy. Robotics and AI are driving innovation in many sectors, including healthcare, manufacturing, transport, space, oil and gas, finance and other service industries. The UK has significant strengths in many of these areas. Accelerating development in these key sectors will ensure that the UK leads in commercialisation, as well as scientific advances.

The first wave of challenges that the UK funding bodies announced include the development of robotic and AI systems that will operate in extreme and hazardous environments, including off-shore energy, nuclear energy, space and deep mining.

Looking at the current robotics and AI landscape, what are the further opportunities and challenges? The first is in manufacturing and services. Manufacturing contributes over £7 trillion to the global economy. Contrary to common belief, the UK is one of the largest manufacturing nations, ninth in the world, with manufacturing accounting for 11% of the national output. We face strong competition from Europe, the USA and Japan, as well as new ambitious foreign competitors particularly in Asia, where there is unprecedented investment in fundamental research and national infrastructure.

Adoption of robotics and AI to enable high-value manufacturing for not only big, but small- and medium-sized companies as well, is of strategic importance. There is also a significant demand for robotics and AI that focus on recycling components and subsystems used throughout the manufacturing process to reduce waste.

Transport is another area that presents challenges and opportunities for robotics and AI. As schemes to pilot driverless cars mature, automated transportation systems and solutions are set to expand from constrained environments such as airports to public transport, urban centres and other general-purpose environments. With the demographic shift associated with the ageing population, robotics will also transform transport solutions for the elderly and those with limited mobility, allowing them and wheelchair users to independently access their own vehicles and public transport systems. As a nation, we may not be able to compete with others in terms of hardware platforms, but we do have a strong competitive edge in the underlying technologies, particularly in machine vision, embedded intelligence, control and verification, which are at the heart of future autonomous transport systems.

Another area is in the use of robotics for space, environment, maritime and deep-sea exploration. In homeland security, law enforcement and defence, improved functionality and sophistication of search and rescue by unmanned systems, augmented by intelligent surveillance and different threat countermeasures, will ensure a rapid uptake of the robotics and AI technologies.

One of the most exciting areas of robotics and AI is in healthcare. Medical robots represent one of the fastest-growing sectors in medical devices. For rehabilitation, robots play an increasing role to provide early support for faster and more complete recovery. With improved safety, efficacy and reduced costs, robotic platforms will soon approach a tipping point, moving beyond early adopters to become standard practices. Other drivers for healthcare robots are the ageing population and the increasing importance of quality of life, independence and autonomy for those with chronic illnesses and disabilities. However, the biggest hurdle for robotics to overcome in healthcare is how to make the technology more cost effective and accessible.

The pursuit of these areas requires synergistic efforts from academia and industry. Establishing our lead in robotics and AI is an opportunity that the UK cannot afford to miss. The future lies in our coordinated effort to establish our niche and leverage the significant strengths we already have, and expand upon those areas that are strategic to the UK.

BIOGRAPHY

Professor Guang-Zhong Yang CBE FREng is Director and Co-founder of The Hamlyn Centre for Robotic Surgery at Imperial College London and Chair of the UK-RAS Network (www.uk-ras.org), which organises UK Robotics Weeks each June. His main research interests are in medical imaging, sensing and robotics.

In the Royal Shakespeare Company's latest production of *The Tempest*, the character of Ariel is partly recreated as a digital avatar while the actor performs live on stage (right of image). Motion-capture technology is used to turn the actor's movements into an animation that flies, spins and whizzes around the stage © Intel

THE TECHNOLOGY BEHIND *THE TEMPEST*

William Shakespeare's *The Tempest* is a fantastical play that features illusion and otherworldly beings. Technology journalist Richard Gray spoke to Sarah Ellis, Director of Digital Development at the Royal Shakespeare Company, Ben Lumsden, Head of Studio at Imaginarium, and Tawny Schlieski, Director of Desktop Research at Intel, about how cutting-edge technology has brought the magic and spectacle to life on stage.

'On a ship at sea: a tempestuous noise of thunder and lightning heard.' From this opening stage direction of William Shakespeare's *The Tempest*, it is clear that the audience is in for a night of electrifying special effects to match the actors' performances. Packed with dramatic storms, a shipwreck and powerful magic, it is perhaps one of the trickiest of the playwright's works to translate from the page to the stage. Written just six years before his death, it has more stage directions than any of Shakespeare's other plays.

Even when performed during Shakespeare's life, the play was a feast of special effects and backstage technology: wheels of canvas spun at high speed and fireworks were used to recreate the sounds of a raging storm; trapdoors made characters disappear; false tabletops made props vanish; and cast members were carried aloft by elaborate pulley systems. While the techniques available to directors have advanced considerably since then, recreating Shakespeare's vision in a live theatre performance has always remained a challenge. Now, four centuries after his death, modern technology may finally be giving theatre-goers a glimpse of the play as Shakespeare originally imagined it.

In its latest production of *The Tempest*, the Royal Shakespeare Company (RSC), in collaboration with Intel and Imaginarium Studios, has used motion capture – a technique that uses cameras and computers to track an actor's movements – live on stage to create a three-dimensional (3D) digital character in front of audiences.

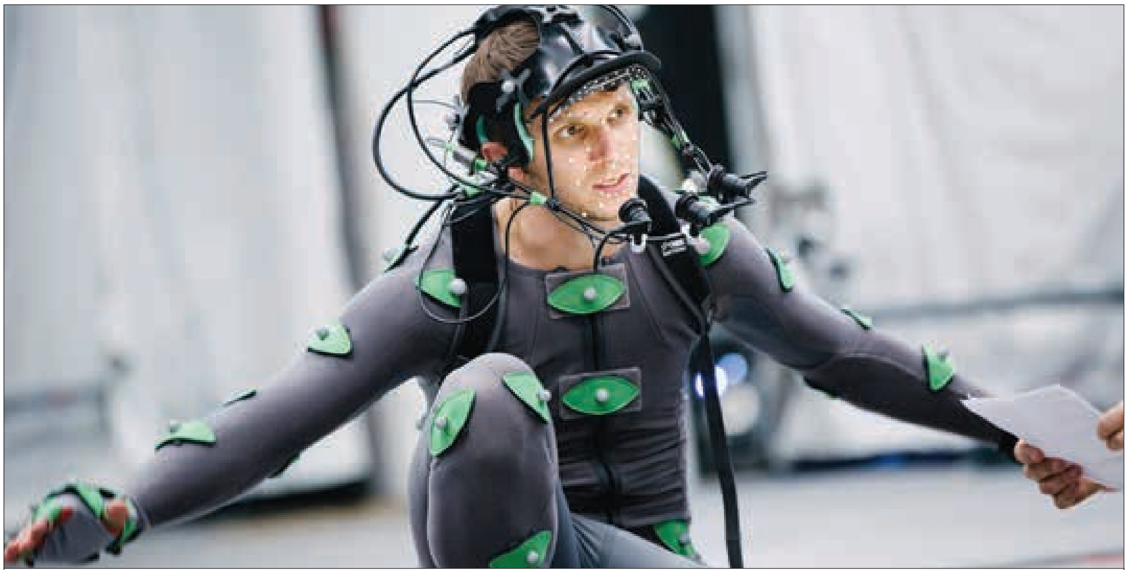
This latest production has just finished a successful run at the RSC's home in Stratford and is due to be shown at the Barbican in London this summer. In the adaptation, the character of Ariel is performed live on stage while motion-capture sensors embedded in the actor's suit turn his movement in real time into a 3D animation that prances, dances and flies above the stage. It allows Ariel to transform into a sea nymph or a terrifying harpy at the command of the wizard Prospero, with the digital character integrated throughout the whole performance.

CAPTURING THE ACTION

Motion capture itself is not all that new. It has been 16 years since Andy Serkis first appeared on cinema screens as the snarling and snivelling animated character Gollum in *The Lord of the Rings* trilogy. His groundbreaking performance in the films brought motion capture to the attention of the world. Serkis wore a special suit covered in reflective markers so that the filmmakers were able to track his movements as he acted out the part of Gollum opposite other cast members. This was then used to map his movements onto the computer-generated Gollum that appeared in the final film.

However, motion capture was not invented or first used by the film industry. It was initially developed in the 1970s as a tool to help analyse how a person walks during rehabilitation sessions following an injury. Healthcare professionals could use cameras to track markers placed on a patient's limbs to precisely model their gait and look for defects. In the mid-1990s, the video games industry saw the potential of motion capture to help it to create more lifelike characters in computer-generated worlds. However, after Serkis's acclaimed performance in *The Lord of the Rings*, the technology's use in the film industry has exploded. Serkis himself has since played dozens of computer-generated characters with the technology in movies including *King Kong*, *Rise of the Planet of the Apes* and *Star Wars: The Force Awakens*.

Traditionally, motion capture has been carried out using passive reflective markers that bounce infrared or near-infrared light back to an array of up to 60 specially adapted cameras. These reflective markers are placed near the joints of an actor's body, allowing the system to pinpoint the position of each body part relative to each other. Mathematical models are then used to map these onto a digital skeleton to replicate the actor's movements on a computer. A computer-generated character, or avatar, can then be superimposed



Motion capture technology involves actors wearing suits covered in reflective markers that pick up their movements
© Intel

upon this skeleton to drive its movements.

In movies and computer games, actors can perform in specially built studios, wearing suits covered in these reflective markers. In the studios, they are shielded from rogue lighting that may interfere with the cameras or electrical interference that could throw off the tracking. There is time to deal with glitches in the software that can mean lengthy computer restarts, while errors in the avatar itself can also be fixed in the production process. There is no such luxury on the stage.

ILLUSIONS ON STAGE

Adapting a technique that is usually used in feature films with long production times to a live stage performance was no easy task. The technology had to be robust enough for eight shows a week in a live environment and work with all of the other technologies used on stage. Initially, the team had imagined projecting the character of Ariel onto the stage while actor Mark Quartley, who plays the 'airy sprite' in the production, would perform the role in a room backstage. It is something that had been done before during *Shrek* on Broadway, when motion capture was used to let an actor perform as the Magic Mirror from backstage. While this would have been a controlled environment where a specialist team could have been in charge of everything that happened, the production's director, Greg Doran, decided that it was important to have the actors acting opposite each other.

While rehearsals went ahead, more than a year's worth of research and development was undertaken to solve the problem. Sarah Ellis, Director of Digital Development at the RSC, asked Tawny Schlieski, Director of Desktop Research at Intel, to help after seeing a video of a computer-generated 1,000-foot whale that Schlieski and her team had created to virtually 'fly' over the audience at a consumer electronics show in 2014.

Schlieski and her team's big digital work had mostly been one-offs until that point. With their work on *The Tempest*, they needed to take the technology and turn it into something where Quartley could turn up just before the show, put on a suit and it would work. The RSC and Intel turned to Serkis's performance capture and production company, Imaginarium Studios, for help transferring the motion-capture technology onto the stage.

One option was to use active markers on the costume rather than passive reflective ones. These use tiny light-emitting diodes that pulse light at a high frequency rather than relying upon light bouncing off the markers. This means that the cameras can be placed up to 40 metres away rather than just 10 metres with the reflective markers, something that would be much more practical in a live stage performance. The only problem with this was that Quartley would have had glowing red dots on his body throughout the performance.

Fortunately, the fast pace of technology intervened with the release of new miniaturised wireless sensors that use a combination of gyroscopes, accelerometers and magnetometers to capture motion in three dimensions. These sensors, known as inertial measurement units, were built into the fabric of the figure-hugging bodysuit that Quartley wears during the play. The technology was initially used to help manoeuvre aircraft and guided missiles, but has now shrunk to the point where it cannot be seen on his body. The gyroscopes help to detect changes in rotation and pitch, while the speed of the movement is detected by the accelerometers. The magnetometers help to calibrate their orientation. In total, 17 sensors were attached to the suit: one on each hand, one on each forearm, one on each upper arm and so on. Each sensor was tethered to a wireless transmitter worn by Quartley that would stream the data back to a router, allowing the engineers to calculate the rotations of his joints relative to each other and get the joint angles. The process is not quite as accurate as using an optical system, but was not problematic as the actor did not need to be tracked around the stage.

Instead, the team focused on tracking the movement of

Four different computer systems were custom built to create the avatar and the different looks of the character of Ariel were created using advanced graphics software, Unreal Engine. The different versions of the character are mapped onto a three-dimensional model of actor Mark Quartley's body, built using data picked up from the motion-capture sensors © Stephen Brimson Lewis (left image) © Intel (right image)

his upper body and mapping this onto the digital characters beamed above the stage. Actions such as making the creature look as if it was flying or swimming could be achieved using pre-programmed computer graphics. Even so, the resulting digital avatar of Ariel has 336 joints that can be animated, which is almost as many as the human body. Powering Ariel's avatar requires more than 200,000 lines of code to be running at the same time. All this takes some formidable computing power.

CHARACTER FROM A COMPUTER

Intel had to custom build four different computer systems to cope. The first purely receives the data from the sensors in Quartley's suit and then passes it to another machine that maps the data onto a digital 3D model of Quartley's body, built up using body scanning. This is then superimposed onto the digital avatar using advanced graphics software known as Unreal Engine, developed by Epic Games for use in high-end video games. This allowed designers to play with the look of the character so that Ariel can appear in different guises throughout the play. Another computer system drives the theatrical control system, ensuring that the graphics produced by the Unreal Engine appear on the right part of the stage at the right time. A final machine powers the video server that is connected to the 27 high-definition laser projectors that show the final images on the stage.

Intel built two identical machines that ran in parallel so that if there was a problem, such as a glitch in the Unreal Engine that would need a restart, the computer engineers could switch to the other machine,

UNREAL ENGINE

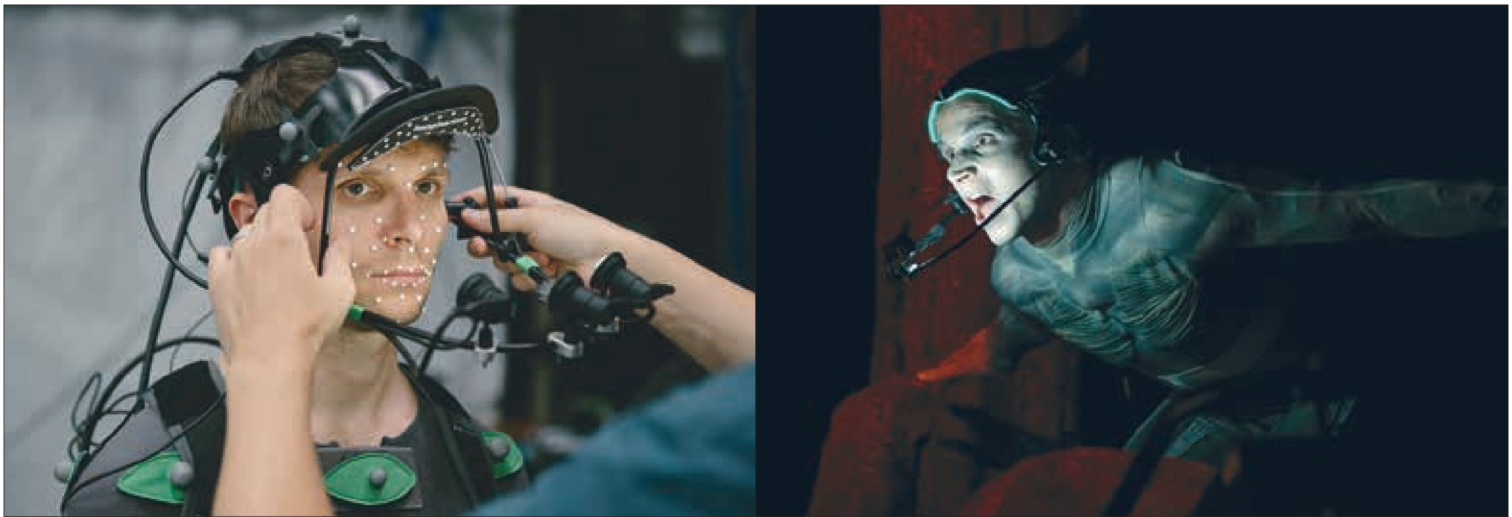
First created by video games developer Epic Games in 1998, the Unreal Engine technology has become one of the most popular tools for creating realistic three-dimensional graphics for games. It features a set of software tools written using the C++ programming language that allow users to animate digital characters, build virtual worlds and replicate realistic physical interactions between animated objects.

For *The Tempest*, designers were able to use the software's powerful animation system to create and control a skeleton around which the body of Ariel could be built. The software allows scans to be imported, so for *The Tempest*, body scans of the actor's body were used.

Other systems within the games engine are then used to add 'flesh and skin' to the skeleton and rendering these realistically by adding colour, texture, lighting, shading and geometry.

Unreal also features a physics engine, which performs calculations for lifelike physical interactions such as collisions, bouncing or movement of fluids. This can help ensure that characters do not simply pass through walls, for example, and was instrumental in ensuring Ariel moved in a realistic way. Lighting systems also allow scenes and characters to be lit in a realistic fashion so that, as they move, the light source remains consistent.

Imaginarium's designers used Unreal Engine to set a series of rules about how characters will be controlled. In a computer game, this can be used to determine how certain buttons used by a player will cause a character to behave, but for the stage it allowed Ariel to be puppeteered by the actor.



To capture actor Mark Quartley's facial movements in real time, Imaginarium built a system to attach a motion-capture camera to his head. Special make-up is used to highlight key parts of his face and the movements are then fed into the computer system and reproduced on his digital avatar © Intel

which would be in sync. This means that there were eight computer systems whirring away in the theatre to produce the digital character of Ariel. The computers driving the projectors had 120 Intel i7 cores placed in server racks – a machine staff nicknamed the 'Big Beast'.

One of the first challenges that the Intel team faced was making sure that the hardware did not melt, which meant keeping the computers away from the sweltering glare of the lights and using a lot of fans to keep them cool. In a theatre performance, which relies on keeping the attention of the audience on the stage, the buzz of these fans and hum of the computers could have been a distraction. Each of the computer servers had to be packed with soundproofing and moved as far away from the stage as they could be. The team also faced another noise problem: the 27 projectors sitting over the heads of the audience would create a cacophony of noise that would be hard to ignore. However, just months before the performance opened, they got their hands on some new laser projectors that could turn on and off silently.

Imaginarium also built its own system for capturing the facial movements of Quartley in real time for a scene during Act III of the play, when Ariel is sent as a harpy to terrify the shipwrecked lords. The team created a contraption similar to a cycle helmet for Quartley to wear on his head during the scene. A metal bar extends from either side of his head to hold a motion-capture camera 20 centimetres away from his face. The team developed make-up for Quartley that would highlight his lips, eyes and other key parts of his face to ensure that the camera could pick up his movements and feed them to the computer system. They also developed algorithms that learned to recognise human faces before training the software on Quartley's own face over several months as he rehearsed the scene. This allowed the designers to work out what the facial expressions Quartley produced would look like on the harpy.

In a neat reversal, Imaginarium expects to use the real-time facial technology developed for *The Tempest* in future feature film productions to allow directors to see their actors' performances rendered onto digital characters on set rather than months later.

The performance of Ariel is not the only motion capture used during the play. The digital avatar is projected onto 14 curved gauze screens that fly in and out of the stage while in the centre there is a gauze cylinder filled with smoke known as the 'cloud', with each screen tracked using optical motion-capture cameras and software. Bespoke software was created by Vicon – a motion-capture technology specialist – and D3 – a video server firm – to track the screens as they moved around. This data is superimposed onto a virtual map of the stage to help ensure that the images are projected onto the right spot, while also guaranteeing that the lighting software and spotlights work in sync with the projections. This system is also used to create other visual effects seen during the performance, including projecting images of dogs onto drums carried by spirits as they chase some of the characters.

To help the production team each night, engineers at the RSC also built controls into the lighting control console used in the theatre so that they could change Ariel's appearance using faders. What they created was a sort of 'avatar mixing desk', which made Ariel disappear or reappear with an analogue fader, change his colour or appearance, or set him on fire and control how much fire. In the end, much of the appearance of Ariel's digital avatar was automated with cues at Stratford, but the engineers

The production's set features an elaborate gauze cylinder in the middle of the stage that uses the motion-capture technology to ensure that projections, lighting and spotlights are synchronised © Royal Shakespeare Company/Topher McGrillis

hope to make more use of the mixing desk approach when the show starts in London.

IRONING OUT PROBLEMS

The final performance is not without its problems. Critics have commented on noticeable lip-synching issues when Ariel sings or speaks and there are also difficulties with the delay that occurs as Quartley's movements are crunched into bits and then back into images, as the games engine, each video server and the projectors all have frames of latency, which cover the time from rendering to display.

Due to the tight production schedule of the RSC, the cast did not begin rehearsing on the final stage until a few weeks before the play opened and there were still some final problems to be ironed out. The very large metal structures within the theatre building meant that there were dead spots where the suit would not track properly as the gyroscopic sensors reacted to the metal, so Quartley had to remap his performance to avoid them.

A technical team also waits on standby in the wings during each performance, ready to recalibrate Quartley's suit when he comes off stage between scenes. Quartley also faced other problems in the final days of rehearsals. The graphics team were tweaking and updating the way the digital character moved almost continually, which meant that he had to change his onstage movements as well to get the avatar to do what he wanted.

The real achievement of *The Tempest*, however, may be to transform the way that stories can be told. Ben Lumsden, Head of Studio at Imaginarium, believes that this sort of live motion capture could be adapted to all sorts of events, such as live music performances and at theme parks, where performers wear sensors under their clothes. It could also be adapted for use by the business world; Microsoft and NASA have already experimented with using live avatars at meetings in place of individuals who are not able to be physically present. The medical industry is also looking at whether the technology could be used in remote consultations between doctors and their patients. It would allow doctors or surgeons to examine a patient in far more detail than might be possible over a simple video link.

For Shakespeare, *The Tempest* was an Elizabethan technological feast that would use state-of-the-art effects to bring his words alive. Now, 400 years later, modern technology has brought even more magic to the stage.

BIOGRAPHY

Sarah Ellis is Director of Digital Development at the RSC. As a theatre and spoken word producer, she has worked with venues including the Old Vic Tunnels, Battersea Arts Centre, Southbank Centre, Soho Theatre and Shunt.

Ben Lumsden is Head of Studio at Imaginarium Studios. He started working on motion capture on the film *District 9*, and his film credits since have included *Avengers: Age of Ultron, Dawn of the Planet of the Apes* and *Star Wars: The Force Awakens*.

Tawny Schlieski is Director of Desktop Research at Intel Corporation. She is a research scientist and media expert in the Intel Experience Group, and her work centres on new storytelling capabilities enabled by emergent technologies.

The near-complete Queensferry Crossing alongside its two neighbours © Transport Scotland

WORLD RECORD-BREAKING BRIDGE

The Queensferry Crossing, Britain's first major new bridge for a generation, is due to open later this summer. The 2.7-kilometre-long crossing is the world's longest three-towered cable-stayed bridge, Britain's tallest bridge, and Scotland's largest construction project in the 21st century. Engineer and writer Hugh Ferguson spoke to Michael Martin, Project Director with main contractor Forth Crossing Bridge Constructors, David Climie, Project Director with client Transport Scotland, and Peter Curran, Director with Forth Crossing JV – the three engineers who were most closely involved in the bridge's construction.

The Forth Road Bridge has been successfully carrying road traffic across the Forth estuary since 1964, but with loads now weighing many times more than what it was designed for and concerns that cable corrosion would force premature closure, a replacement became an urgent necessity. Although many options were considered, the choice was straightforward in the end. A modern cable-stayed bridge was far cheaper and quicker to build than a tunnel or a suspension bridge, and a location close to the existing bridge made connections into the existing road network far easier. The clincher was Beamer Rock, a natural outcrop in the middle of the Forth that provided the ideal location for the central tower of a three-towered cable stayed bridge.

MODERN DESIGN

The design for the new bridge was initially developed by Transport Scotland's (TS) consulting engineers Jacobs Arup, led by Arup's global bridge design practice leader Naeem Hussain (who was awarded the Royal Academy of Engineering's Prince Philip Medal in 2012 for his groundbreaking work on bridges, including Queensferry). The final design was developed in a joint venture between Ramboll, Sweco, and Leonhardt, Andrä und Partner, while construction was the responsibility of Forth Crossing Bridge Constructors (FCBC).

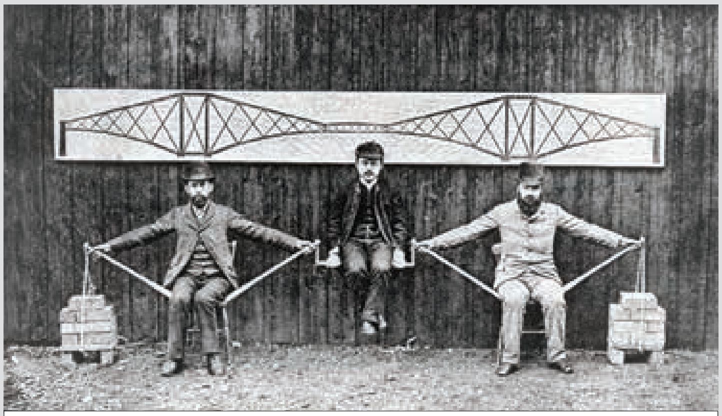
The bridge's form sits in harmony with its two well-known neighbours, each representing the pinnacle of bridge engineering of its generation. The design's most distinctive – and unusual – feature is the crossover of the cables at the middle of each span. This stems from a peculiarity of three-masted cable-stayed bridges: as the central tower is not connected to a stiff back-span structure (which would reduce any twisting), an out-of-balance live load on just one of the main spans can cause large deflections in the central tower and deck, and large bending movements in the tower. This can be countered, for example, by making the central tower larger and stiffer, making the deck much deeper and stiffer, or by tying the tower tops together with additional cables. A much more elegant, and economical, alternative was to design the stay cables to overlap over almost a quarter of each 650-metre-long main span, which effectively adds greatly to the stiffness of the deck without increasing its size. This has never been done before on a large bridge.

ENGINEERING PRINCIPLES OF BRIDGES

Simple cantilever bridges, which project horizontally into space and are supported at only one end, are as old as civilisation, but in the late 19th century, engineers began to explore the potential for combining the cantilever principle with steel trusses to span much larger distances, notably on the Forth Bridge.

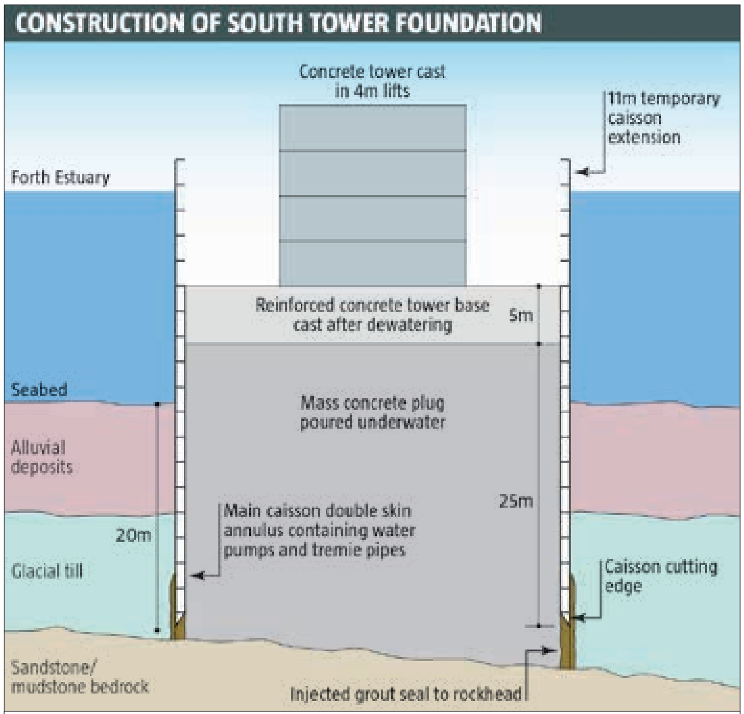
A suspension bridge has suspension cables hung from two or more towers that are held by massive anchorages at the ends. The cables support hangers, which in turn support the deck. Origins may be traced back to ancient rope bridges, but the modern suspension bridge emerged with the application of iron to provide a robust long-span bridge, such as Thomas Telford's 176-metre-span Menai Bridge in 1826. Wire cable replaced chain links, which led to a series of great US suspension bridges, most famously the 1937 Golden Gate Bridge with its 1,280-metre main span. The Forth Road Bridge marked the start of British dominance of suspension bridge design, including the 1981 Humber Bridge with its (then) world's longest span of 1,410 metres. Later, Japanese engineers took the lead: the 1998 Akashi Kaikyo Bridge still has the world's longest span at 1,991 metres. Suspension bridges remain the form of choice for the very longest spans.

A cable-stayed bridge has one or more towers from which cables support the deck, in either in a fan-like pattern or a series of parallel lines. They have been in development since the 16th century and used widely since the 19th century, sometimes in conjunction with suspension cables, such as New York's Brooklyn Bridge or London's Albert Bridge. They fell out of favour in the 20th century, but enjoyed a resurgence from the 1950s as new materials and equipment and more sophisticated analytical techniques lowered their relative price – notably for rebuilding large bridges in Germany under pioneers such as the structural engineer Fritz Leonardt. They have become established as the form of choice for a wide range of long spans.



Benjamin Baker staged this 'human cantilever' photograph with three of his engineers in 1887. The photograph neatly illustrates the structural principles of his Forth Bridge. The short central suspended span, which is holding up engineer Kaichi Watanabe in the centre, is supported by two of the huge cantilever towers: the compression members are represented by wooden poles and the tension members by the men's outstretched arms, while the bricks represent the use of the end piers as anchors to provide stability © courtesy of the Institution of Civil Engineers

A cylindrical caisson for the tower foundations is floated out by barge and lowered into place on the seabed by shear-leg crane © Transport Scotland



The bridge's tower foundations were built within huge double-skinned steel caissons. A four-metre-high section of concrete was poured in, before the mould was lifted and re-fixed for the next section to be poured – a process that took up to two weeks © Transport Scotland

This design formed the basis of consultation and planning, and the subsequent Bill received Royal Assent in January 2011. Meanwhile, bids were invited to do both the detailed design for the bridge and its approaches, and the construction. Tenderers were given a set of 'definition drawings' that indicated the requirements for the overall form and geometry of the bridge, including the shape of the 'mono-towers' and the arrangement of the cables in two lines down the centre of the bridge, together with a 'specimen design' that gave an example of how all other aspects could be designed. In early 2011, the contract was awarded to FCBC and its designers for £790 million, for completion by the middle of 2017.

FCBC's early decisions included opting for a composite design for the trapezoidal box sections of deck for the bridge and approaches (steel with a concrete top, rather than all steel or all concrete); ordering all major steel components from overseas fabricators in China and Poland. Perhaps most surprisingly – and successful – the engineers chose to service the site and its remote locations in the sea by investing in a 30-strong fleet of floating plant, rather than (as expected) building causeways for road access from the shore. This approach saved both time and cost.

WORKING UNDERWATER

The first onsite task was to create the foundations, particularly for the three main towers. As with the bridge's earlier neighbours, the foundations presented an even greater challenge than the more visible superstructure, and represented around 30% of the total cost. The central tower on Beamer Rock was relatively easy to construct, but the other two had to be sunk through deep water and soft ground to rest on the solid rock beneath. For these, FCBC chose some of the largest steel caissons (large cylinders that were lowered onto the seabed and had thousands of cubic metres of concrete poured into them, which the tower foundations could be laid on top of) ever used in bridge construction.

The largest, for the south tower, was 30 metres tall and 32 metres in diameter, double-skinned with a 400-cubic-metre volume annulus (a ring-shaped structure) between (capped with temporary steel plate so that the air inside provided buoyancy while towing and placing), and a cutting edge at the bottom. This was then carried out into the estuary on a semi-submersible barge, which was partially sunk beneath the caisson, hooked up to a large shear-leg crane. It was then towed into position where it had to be located with 200 millimetres accuracy; a feat that was not easy in a fast-flowing tidal estuary, even with the help of GPS. By slowly releasing air from the annulus, the caisson was gently lowered to the seabed. Concrete was added in the annulus so that it would sink until it was embedded firmly in the soft sediment deposit below. A separate 11-metre-tall single-skin cylindrical steel caisson was then bolted on top so that it would extend above water level as the caisson was sunk further.

The sinking stopped when a corner of the cylinder reached the sandstone bedrock. The perimeter of the caisson was sealed into the rock by a ring of interlocking jet-grouted piles and the remaining soft material was dredged out to expose the bare rock beneath. But then came the most difficult and time-consuming bit of all: vacuum cleaning and minutely inspecting the rock head (in deep, murky water with little visibility) to ensure it was clean and free of large cracks.

Once this was done, the bridge's foundations could be created on top of the rock head by pouring tremie (underwater) concrete to fill the inside of the caisson. For the south tower foundation, this was a continuous pour of 16,900 cubic metres of concrete over two weeks, supplied by a fleet of barges that worked around the clock from the quayside batching plant. (This was a world record for an underwater marine concrete pour.)

This brought the foundation up to around 15 metres below water level. The remaining water was pumped out and a five-metre-thick reinforced concrete tower base was built on top. Once this was completed, construction of the towers could commence. The hollow, elliptical, tapering heavily-reinforced concrete towers were formed in 'jump lifts': a four-metre-high section would be poured using concrete ferried by barge from the shore and pumped in. The moulds were then lifted and re-fixed ready for the next pour. Each lift took about seven to 14 days.

As the concrete tower continues skywards in four-metre 'jump lifts', the first deck sections are placed on massive steel falsework round the tower base, and traveller cranes lift new sections into place either side, with the first stay cables already installed © Transport Scotland

DECK ASSEMBLY

Meanwhile, all 122 steel troughs for the deck were taking shape in a Shanghai fabrication yard, overseen by a team of engineers from TS and FCBC. Each 250-tonne trough was match-fitted to its neighbour in the factory before being disconnected and transported to Rosyth Docks. Once it reached the docks, reinforced concrete deck up to 460 millimetres thick was added, increasing the weight to around 700 tonnes, before each 4.5-metre deep and 40-metre wide box-section unit could be barged to site.

One of the most awkward tasks was placing the first sections of deck, once the towers had risen above deck level. First, a giant 1,200-tonne-capacity floating shear-leg crane was used to erect a huge temporary structure around each of the tower bases. The structure consisted of two 146-tonne raking triangular trusses (supports) topped by temporary steel platforms. The crane raised the first deck sections and lowered them on to the platforms round the towers and then lifted a traveller crane on to either end.

Each section of deck was floated out from Rosyth on a barge, lifted up by the traveller crane on a rising tide, placed with precisely the right level and inclination (computer controlled to within two millimetres), and bolted into position. As the tower rose and the deck moved outwards, the first of the 288 cables were installed and

In October 2016, the central tower and the deck either side were recognised by Guinness World Records as the longest free-standing balanced cantilever in the world. Shortly afterwards, the gaps at the ends were closed and the cantilevers were no longer free-standing © Transport Scotland

tensioned. Each cable consists of up to 109 seven-wire strands encased in a white polyethylene weatherproof sheath up to 315 millimetre dia. The first strand was lifted with the sheath and stressed to 10 tonnes by jacking crews on the towers. The other strands were then pulled through the sheath and stressed one by one. Although stressing could be done within the towers, positioning the cables and threading the strands at the tower tops was done by workers in open baskets hoisting themselves on wire supports up the outside face of each tower, one of the most weather-sensitive operations of the whole project. Eventually, just before the decks met at mid-spans, the central tower and the deck on either side were recognised by Guinness World Records as the longest free-standing balanced cantilever in the world.

The crossing's most dramatic moment was the closure of the mid-spans. Vertical differences between the two adjacent cantilevers could be as much as four metres before final balancing, which was achieved by a combination of repeated tweaking of the stresses in the cables and the less sophisticated process of shifting the location of plant and ballast on the decks to alter the balance. Using jacks, one side of the deck was 'pushed' landwards by 300 millimetres to make space for the final deck section to be lifted in place and fixed on one side, while several hundred measurements were coordinated by computer software that monitored real-time loadings, stresses, orientation and global positioning. Work was suspended if wind speeds reached over six metres a second. Releasing the jacks closed the gap to just five millimetres, and the join was completed by bolting, welding and a concrete 'stitch' at deck level. The crossover cables were then added, with a complex sequence of stress readjustment on nearby main cables.

WEATHER IMPACT

The team had known from the start that weather – particularly high winds – would play a major part in the programme: for example, a deck lift required a four-hour weather window with wind speeds less than 14 metres a second, and less than 11 metres a second for positioning and stressing the cables at the tower tops. However, it was felt that good and bad periods would even themselves out, which proved correct for the first few years.

Caisson sinking was delayed by bad weather, and there were further delays in grouting the seals beneath the caissons and cleaning the rock head. Acceleration measures were introduced, notably increasing the number of traveller cranes from four to six so that deck erection around each tower could operate in parallel rather than in sequence. However, erecting the falsework structures around the towers was much quicker than expected, thanks to benign weather in autumn 2014. Up to the end of 2015, total downtime due to weather was around 25%, close to original expectations, and an early opening date at the end of 2016 was being confidently predicted.

In 2016, at a time when wind-sensitive operations were at their peak, tower construction and cable anchoring were delayed by unrelenting high winds. Deck erection and the dismantling of temporary works were also affected, and weather-related downtime in 2016 was 40%. The winter of 2016–17 was particularly frustrating: mild, but with periods of exceptionally high winds, which meant that 20 days were lost to wind in February and 16 days in March. The removal of the first tower crane, normally a two-week job, took 65 days. The opening date for the crossing was put back, which created an unfortunate impression of delays. However, completion is now scheduled to be only 10 weeks beyond the date agreed some six years earlier.

BRIDGE TO THE FUTURE

So far as possible, the crossing has been future-proofed. An extra lane or bus lane can be added to the road layout, currently a dual two-lane with wide hard shoulders. The bridge has louvred wind-shielding at 3.6 metres high along its whole length to prevent closure during high winds. A continuous walkway inside the bridge deck will help maintenance be carried out when needed, while the insides of both of the deck boxes and towers are continuously dehumidified to prevent corrosion of the exposed cable anchorages. The cables themselves are well sheathed, but individual strands or even whole cables can be removed, if needed, and replaced without interrupting traffic. The whole bridge is wired up with several thousand accelerometers, anemometers, temperature sensors, corrosion cells, GPS/biaxial tilt meters, and dynamic and static strain gauges so that a picture can be built up of the bridge's performance in all combinations of wind, temperature and traffic loading. The bridge is intended to last for a very long time.

Like its neighbours, the Queensferry Crossing has paved the way in innovative engineering, and the three bridges across the Forth should provide a fitting monument to engineering achievement for many years to come.

FORTH BRIDGE

A symbol of Scotland and one of the wonders of the late 19th century, the three-tower four-span Forth Bridge, with its distinctive cantilever-and-beam design, is one of the most instantly recognisable structures in the world. Its two main spans of more than 500 metres were the world's longest cantilever bridge spans when it opened in 1890, and remain the second longest. The railway bridge was also the first major structure in Britain to be constructed in steel.

Railway engineer Sir Thomas Bouch's original design was for a slender, twin suspension bridge. Clydeside iron and steel fabricator William Arrol had already started work on the foundations when, in December 1879, Bouch's Tay Bridge collapsed while a train was crossing, killing all 75 passengers and crew. Bouch's Forth Bridge design was quickly abandoned, and civil engineers Sir John Fowler and Sir Benjamin Baker were commissioned, with Arrol as fabricator and contractor.

Challenges included fabricating the huge compression tubes from multiple flat plates and devising a construction sequence working outwards over the water from the piers that was stable at every stage. The greatest challenge lay in the 'invisible' work in the foundations. For the difficult south pier, four huge steel caissons (cylinders) were weighted and slowly sunk as the clay was hand-dug beneath, with the workers protected from incoming water by a novel design of compressed air locks by Baker and Arrol. The only serious mishap on the project came when one of these caissons tilted and slipped during sinking, causing 10 months' delay.

From the start, a full-time maintenance crew looked after the bridge, leading to the expression that any never-ending job is 'like painting the Forth Bridge'. The painting never was continuous, and the myth was finally exploded when the latest major refurbishment was completed in 2011. Grit blasting was followed by a three-part coating system that culminated in the trademark topcoat of 'Forth Bridge Red' ('Restoration of the Forth Bridge', *Ingenia* 49), which should last at least 20 years.

Construction of one of the beam sections that connect two of the Forth Bridge's giant balanced cantilevers in the 1880s © courtesy of the Institution of Civil Engineers

FORTH ROAD BRIDGE

The Forth Road Bridge was designed (jointly with Mott Hay & Anderson) by a team of engineers at Freeman Fox & Partners led by Sir Gilbert Roberts. It was the first in a sequence of bridges that included the Severn, Bosporus and Humber. Forth was one of the many estuarial road crossings that formed part of the reconstruction plans drawn up during the war, but was delayed by post-war austerity. It was 1958 before work could start, and 1964 before it opened: at the time it had the longest suspension span outside the USA at 1,006 metres. Appropriately enough, the joint-venture contractor included Sir William Arrol & Co, the builders of the Forth Bridge.

Much of the technology was borrowed from the USA, where most of the expertise in design and construction of large suspension bridges resided. This included the steel stiffening truss that supported the deck to counter oscillation under sustained wind loading – the revolutionary Freeman Fox aerodynamically shaped steel box-section deck followed later on the Severn.

The aerial 'spinning' of the main cables wire-by-wire (32,000 miles of it) was also a well-tested US technique. Each of the two main cables consisted of 11,618 galvanised high-tensile wires, bound into 37 strands, which were then compacted and tied together to form a single two-foot diameter cable. Corrosion protection was provided by galvanising each wire, close compaction, red lead paste, wire wrapping and painting. The weather in the Forth estuary delayed the process: weather losses in cable spinning averaged one third of the total time.

Workers on top of a tower of the Forth Road Bridge in 2010, with the new dehumidification system for the cables in place and work progressing on the 'final' repainting of the Forth Bridge in the background © Transport Scotland

The bridge was designed for a capacity of 30,000 vehicles a day in each direction for 120 years, but as traffic increased to many times this level, concern rose about the bridge's lifespan. In addition, discovery of corrosion of cables in older US suspension bridges in 2003 prompted an inspection of the Forth's cables. External inspection had previously shown no sign of problems, and the cables had been regularly repainted, but when sections of the cable were opened up by driving wedges between the strands, a large number of wires were severely corroded, and it was estimated that 8% to 10% of the cables' strength had already been lost. Furthermore, projections of further corrosion suggested that loading restrictions would need to be put on the bridge by 2014, with full closure a few years later.

An ingenious system for preventing further corrosion was devised, based on the knowledge that no corrosion will occur if humidity adjacent to steel is kept to below 40%. Dehumidification had been used before – including in the cable anchor chambers at Forth – but using the technique for a cable was something of a novelty. The cable was sleeved in a waterproof elastomeric wrap, and then very dry air was pumped in at low pressure through several injection sleeves in each cable, passing along the cable before being released at exhaust sleeves. Further inspections proved the method's success. A further alarm came in December 2015 when two cracks were found in vertical steelwork of the truss supporting the deck, causing a complete closure of the bridge while repairs were made.

Dehumidification cannot restore strength already lost to corrosion, but it has extended the bridge's life at full load at least until the opening of the Queensferry Crossing, after which it will become primarily a public transport corridor with much lower loads.

BIOGRAPHY

Michael Martin is Project Director at Forth Crossing Bridge Constructors, the contractors on the Queensferry Crossing Project. He has worked with Arup and Morrison Construction on many of Scotland's great bridges including Kessock, Kylesku and Dornock Firth Crossing.

David Climie is Project Director for client Transport Scotland and has worked on the construction of many major bridges, including the Forth Road Bridge strengthening, Tsing Ma Bridge in Hong Kong, Storebaelt Bridge in Denmark, and Jiangyin Bridge in China.

Peter Curran is Forth Crossing Design JV's Director and International Bridge Director at Ramboll UK. He has spent his career with Gifford (now part of Ramboll) on projects including the Gateshead Millennium Bridge and the Twin Sails Bridge in Poole.

Hugh Ferguson also talked to Lawrence Shackman, Project Manager at Transport Scotland, and Ian Cookson, a senior engineer at Forth Crossing Bridge Constructors.

AN AIRCRAFT LIKE NO OTHER

Testing an aircraft that is the size of the Airlander in private is impossible, so the first test flight in August 2016 was watched by a crowd of onlookers at the former RAF station in Cardlington, Bedfordshire, which is home to the craft © Hybrid Air Vehicles

The Airlander made headlines when it embarked on its first test flight in August 2016 as the world's largest aircraft. Science writer and broadcaster Geoff Watts talked to Chris Daniels, Head of Partnerships and Communications at Hybrid Air Vehicles Limited, and David Burns, Airlander's Chief Test Pilot, about the engineering that helped it reach this stage and plans for the craft's future.

For more than a century, airships of various kinds have been seeking a sustainable commercial role. So far, no venture has lasted indefinitely, but now, British company Hybrid Air Vehicles (HAV) is confident that it has found the way forward. New materials, new technologies, and most importantly, new thinking have combined to produce the newest breed of airships: a 92-metre craft called Airlander 10. Its capacity for landing anywhere without large numbers of ground staff and, if necessary, staying airborne for weeks at a time offer clear advantages in performing all sorts of tasks.

Unusually, Airlander combines the features of traditional airships with others derived from heavier-than-air machines. Not all its lift is provided by the buoyancy of the gas within its hull: up to 40% is a product of its aerodynamic shape. It is this innovation in aeronautical engineering, its hybrid status, that HAV believes will allow Airlander to rise above the weaknesses that have eventually sunk so many previous forays into this most eye-catching form of transport.

UNUSUAL DESIGN

Seen from the side, Airlander looks like most other craft of its kind. However, the view from any other angle reveals it to be quite different. It has an oval rather than round cross-section, while it resembles a pair of fat sausages pressed side to side when viewed from the front. When seen from the rear, those two sausage shapes have morphed into three. This configuration creates an aerodynamic shape and the forward movement of the craft generates lift.

The origins of this innovative design lie with the late Roger Munk, a British engineer born in the late 1940s, who became fascinated by airships and then set out to find a way of making them a mainstream transport system. One of Munk's inspirations was Sir Barnes Wallis CBE FRS, who had worked on airships and headed the design team responsible for the R100, a craft that had intended to offer mail and passenger services to the countries of the British Empire but was grounded after a flight to and from Canada in the 1930s. Sir Barnes told Munk that the future success of airships would depend on overcoming a clutch of key hurdles. These ranged from the use of stronger and lighter plastics and composite materials to the introduction of more advanced flight control systems.

Over the years, Munk tackled them all. His key insight was the feature that sets Airlander apart from its predecessors: its

AIRLANDER: A BRIEF HISTORY

Airlander 10's manufacturer, Hybrid Air Vehicles (HAV), was set up by Roger Munk in 2007. Its first customer was the US Army who needed an unmanned aerial surveillance craft for use in Afghanistan. The craft had to be able to fly for long periods, and at altitudes of up to 20,000 feet, out of range of local weaponry. HAV was to asked complete its part in the $500-million-dollar programme in the extraordinarily short period of 25 months. It did so, and a successful test flight of what was then called the HAV 304 took place in New Jersey, USA, on 7 August 2012. It was to be the only such outing. Defence budget cuts and the US government's increasing determination to get out of Afghanistan led to the demise of the programme. By the time it was axed, $300 million had already been spent.

HAV saw its chance. The company had a proven craft for which the development costs had been paid, but for which the US Army no longer had a use. There being no competing bids, HAV was able to buy the craft back for a mere $301,000, virtually scrap value, and less than it cost to dismantle it, roll it up, and ship it across the Atlantic. On arrival in Cardington in December 2013, it was repaired, reassembled and reinflated. Some 500 modifications later, and with the support of private investors and grants from the UK government, Airlander 10, as it was now called, was ready for its first test flight.


From the back, the Airlander resembles three sausages that have been squashed together, an arrangement that creates an aerodynamic shape, which is assisted by two top fins and two lower fins – one of which can be seen before it was attached to the hull © Hybrid Air Vehicles

AIRSHIPS BY TYPE

Airships or dirigibles
Any powered aircraft that is steerable, and inflated with a gas lighter than air.

Blimp
A powered, steerable, lighter-than-air vehicle with no rigid internal structure. Its shape is a consequence of the pressurised gas within it.

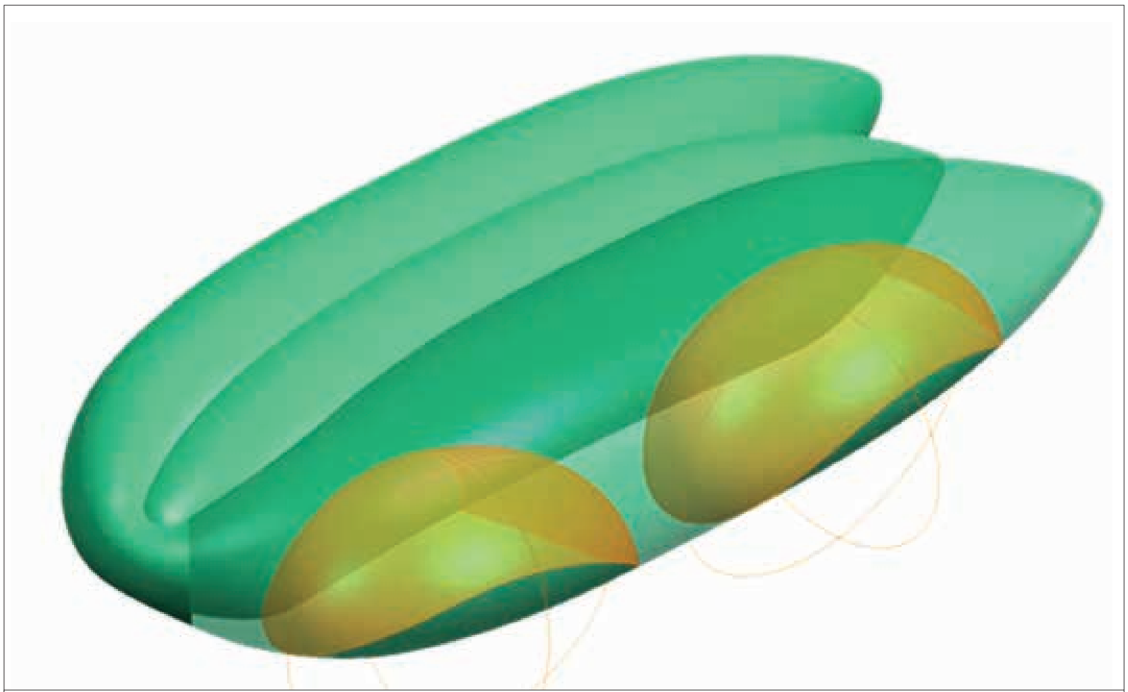
Semi-rigid airship
An airship incorporating a limited rigid frame, typically a keel, to support it and distribute loads.

Rigid airship
An airship with a shape fully defined by a complete internal framework.

Hybrid airship
An airship that relies on aerodynamics as well as the gas within it to provide lift.

mode of flight. While traditional airships, almost by definition, have relied on their inherent buoyancy, Airlander is slightly heavier than air and its default direction of free movement is not up but down. Only when in motion does it generate the lift it needs to start rising. Airlander combines the cost efficiency of an airship, with some of the performance virtues of an aircraft.

Unlike most of its large predecessors, Airlander has no internal framework. Its shape derives entirely from the pressure of the gas within its hull, which comprises some 7,000 square metres of fabric made up of multiple layers of three materials: Vectran, a fibre spun from a liquid crystal polymer and often used in high-performance sails; Mylar, a tough polyester film to ensure that the envelope (structure) is helium-tight; and Tedlar, a vinyl fluoride polymer with good resistance to weather and chemicals. These materials were heat-welded to form a single thin, flexible yet remarkably tough sheet. Delivered to the manufacturing site in rolls, it was cut to shape before the individual sections were assembled by heat-welding. Most existing airship hulls have been made out



Airlander has four ballonets (seen in yellow), or air-filled balloons, within its hull. These serve to maintain the helium in the hull at a constant pressure difference with respect to the outside air. At ground level the ballonets, which are made of the same material as the outer fabric and connected via four vents to the exterior, occupy up to a third of the volume of the craft. As the craft rises and the outside air pressure falls, the helium expands, expelling air from the ballonets, while on descent the reverse happens. The movement of air into the ballonets is aided by large fans set in the openings to the exterior © Hybrid Air Vehicles

of polyester, which can stretch when subject to pressure, but the material used to construct the Airlander is more resilient.

Weight and strength are key factors when making the choice of any components for an airship, not just for envelope of the hull. HAV used Forward Composites to make many of the larger components of Airlander's rigid structures. The carbon and glass composites needed for some of the structure behave differently when pulled in different directions. This has necessitated careful structural analyses to determine how many layers of material were required at specific locations.

The risks posed by a hull filled with hydrogen are obvious, so Airlander uses helium, which is an inert gas. Its pressure, continuously monitored by instruments within the hull, is set only 0.15psi (pound-force per square inch) above atmospheric, so that any leak that might develop would be slow. Moreover, the interior of the hull is divided into 15 compartments that are linked by valves that normally allow the helium to move freely between them, but can be closed if required to isolate individual sections. In contrast with the high-tech materials science that underpins the fabric of the envelope, the methods for detecting punctures in it are more traditional. One is to shine a bright light on its outer surface while observers inside the hull scrutinise its inner surface, looking out for chinks of light. Another is to spray the exterior surface with a soapy solution and look for emerging bubbles. Any repairs that are needed are fixed with a heat-welded patch.

Although it is the second most abundant element in the universe, helium is relatively rare on Earth and mostly produced by the radioactive decay of thorium and uranium. It can be found in varying amounts (from 7% down to nil) in natural gas. Although helium is a finite resource, HAV insists – in spite of occasional claims to the contrary – that we are not yet in imminent danger of running short of it.

THE CRAFT IN FLIGHT

Airlander is powered by four 325 horsepower turbocharged engines with variable pitch propellers. These engines, which use standard aviation fuel, are lighter than those available to previous generations of airship designers. Even so, the absence of any rigid interior framework means that each must be attached directly to the fabric envelope of the craft. Close inspection of the hull next to the forward engines mounted on either side of the craft reveals virtually no sign of the local distortion to its shape that might be anticipated. The remaining two engines, each mounted on the conical rear tips of the hull, are supported by forward-running carbon composite battens, which also support the shape, attached to the fabric of the craft.

The forward engines on the current prototype Airlander can be swivelled by up to 30 degrees from a horizontal position to provide it with vectored thrust. (On later models the engines will be able to swivel through 180 degrees.) Butterfly vanes mounted behind the propellers also allow the airflow to be directed at will. Two side fins and two top fins with rudders are attached directly to the fabric of the hull, and stabilised by Parafil cables, a type of low-weight, high-tensile-strength synthetic rope that typically comprises a closely packed core of parallel

Four 325 horsepower turbocharged engines with variable pitch propellers power the Airlander. They are lighter than engines that were used for previous generations of airships and the absence of a rigid interior framework means that they need to be attached directly to the fabric structure of the craft © Hybrid Air Vehicles

polyester fibres encased in a durable black polymeric sheath.

At speeds of up to 30 knots, the craft is mostly steered by engine thrust. Above 30 knots, steering relies on the rudder and elevators on the lateral fins. The Airlander 10 is not currently intended to take off and land vertically, although the company believes it probably could and later production models will most likely include this facility.

Airlander's payload module and fuel tanks are attached directly to the underside of the hull, which has a curtain of material and an array of strengthening wires connecting it to the hull's upper surface. It can carry up to 10 tonnes of cargo or passengers, and immediately forward of where this is carried is the flight deck with seats for a pilot and co-pilot or engineer. The avionics are as advanced as those of any modern aircraft, but adapted to take account of a very different mode of flight. The central electronic control system connects with the engines, the rudder, all other mechanical components and with remote instruments and sensors via a fibre-optic cabling system. The HAV 304, which Airlander was derived from was among the first aircraft to use this 'fly by light' system, as it has been dubbed. Much of the seven kilometres of Airlander's cabling runs on the craft's outer surface, making it easier to access and maintain. When the British company (AVOptics) that manufactures the system was originally contracted to work on the airship, it found itself having to make cables ten times the length it was accustomed to.

Using a pair of skids running lengthwise beneath it, the craft can land on any surface. Pilots can practise this and other manoeuvres on the company's custom-made flight simulator. Professional simulators for training airship pilots are, not surprisingly, pretty rare. HAV's own simulator has undergone adaptations in which pilots found themselves teaching the simulator rather than vice-versa. The experience of a take-off is not unlike that of an ordinary aircraft but in slow motion, and as with large sea-going ships, the response to adjustments of the controls is not instantaneous.

Although Airlander can operate anywhere from the tropics to the Arctic, it is not wholly immune to weather conditions. Its 30 tonnes of weight give a stability that allows it to function even in ground winds of up to 80 knots. The absence of any rigid internal framework makes it less susceptible to the bending forces of side winds that could be a problem for previous generations of airships.

AIRLANDER 10: THE BASICS

Length: **92 metres**
Width: **43.5 metres**
Height: **26 metres**
Volume of hull: **38,000 cubic metres**
Total weight: **20,000 kilograms**
Altitude: **4,880 metres**
Cruising speed: **80 knots**
Payload: **10,000 kilograms**
Range (with full load): **3,000 kilometres**
Engines: **Four with 325 horsepower turbocharged V8 direct injection**

The auxiliary landing system was added to the craft following its crash. The system, a pilot-deployable two airbag landing system that acts as an extra cushion to land on, allows the aircraft to land safely at a greater range of landing angles. The airbags are over three metres in length and contain 15 cubic metres of gas (less than 0.1% of the entire hull volume) and are situated on each side of the flight deck to offer enhanced protection to the cabin and flight deck. The system uses the existing ballonet fans to inflate, and takes under 20 seconds to be ready for use © Hybrid Air Vehicles

FROM TESTING TO OPERATION

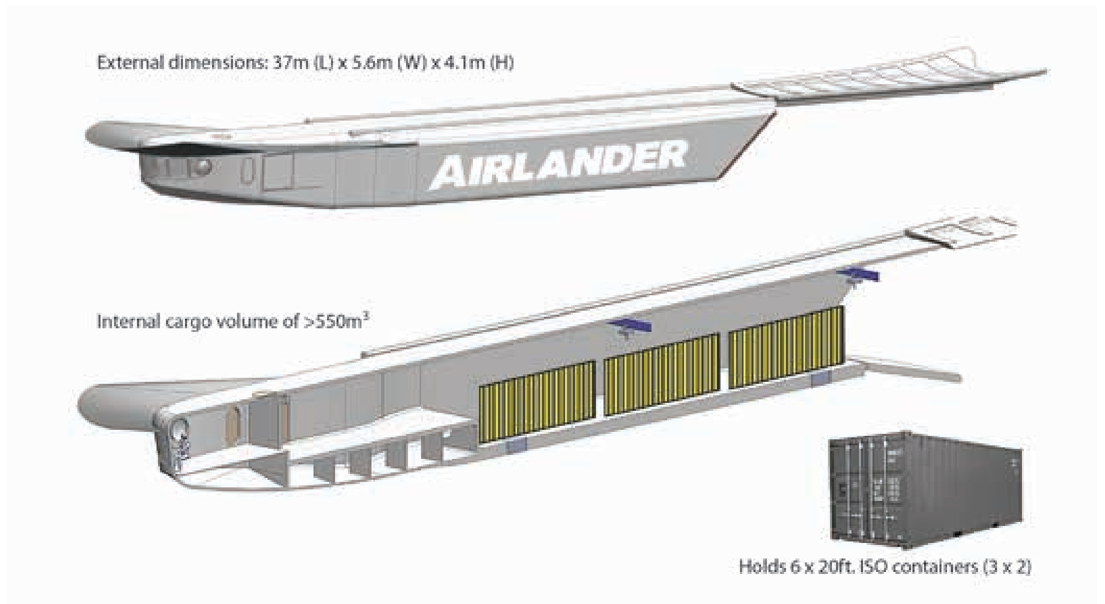
Airlander 10's first test flight, carried out on 17 August 2016 was a complete success. Its second was less so, with the aircraft crashing into the ground as it attempted to land. The hard landing caused no harm to either member of the crew, but severely damaged the control cabin and delayed the test programme by some six months, possibly costing the company £2 million. Fortunately, some of the testing was able to continue while repairs to the cabin were underway. Although all of Airlander's systems continued to operate after the crash, there were lessons to be learned. HAV knows exactly how and why the accident occurred, and is confident that it will not be repeated. Either way, Airlander 10 has now been fitted with an auxiliary landing system: in essence a pair of giant air bags located slightly ahead and to either side of the flight deck. These will be routinely deployed immediately before most landings, rather as an aircraft lowers its undercarriage.

On 10 May 2017, Airlander resumed its Flight Test Programme with a successful three-hour flight. The flight test consists of three phases, during each of which Airlander flies further from its airfield and pushes its speed, altitude and endurance, among other variables, a little further each time. Flight testing will last for a number of months before a series of customer trials and demonstrations begins.

Assuming that the reactivated test programme runs to time and uncovers no major problems, HAV hopes to have the first production Airlander ready for use by early 2019. It currently has over 2,000 shareholders and aims to increase investment, which is expected to happen once the aircraft is flying – an opportunity that the company has not previously had. With the aircraft flying and customer engagement driving forward, the intention is to raise £15 million to fund the early stages of production, with the aggregate level of funding required to support the move to full production at £70 million. Once production has begun, the company plans to list on the stock markets to secure the balance of funds needed.

The operation at the Airlander's base in Cardington, Bedfordshire, is essentially an assembly process, with engines, fabric and so on brought in from elsewhere. The company anticipates being able to manufacture 12 Airlander 10s a year. It envisages them finding a role in surveillance by law enforcement agencies or the military, for oil and gas pipeline surveys, or for luxury tourism (for example, seeing the Grand Canyon from the air). However, the initial production run is expected to be focused on an endurance-optimised Airlander that will provide a platform for patrol, search, survey, communications and filming. HAV believes that the biggest market will ultimately be in cargo but that may have to await the development of larger models.

An independent study by the aerospace consultancy firm Renaissance Strategic Advisors talked of a $50 billion cargo market for airships over a 20-year period, and a need for perhaps 600 craft. It also suggested that success in the cargo field might have to await the advent of a 50 tonne payload. With this in mind, HAV already has outline plans for an Airlander able to carry a payload of 50 tonnes in the form of half a dozen 20-foot containers. However, the size of the potential market remains a matter for speculation, not least because a new combination of longer transit time but lower cost might create a case for moving certain goods – perishable foods, for example – that seldom make long journeys at present, or do so only in small quantities.



The proposed payload space of the Airlander 50, a cargo carrying aircraft that will be able to transport 50 tonnes
© Hybrid Air Vehicles

The operational efficiency of airships is indisputable. They require no runway and little ground infrastructure, and even without vertical lift-off can manage with a space around four times their own length. While helicopters have an operating range measured in hundreds of miles, airships can beat that by an order of magnitude. Their low fuel consumption per unit of payload gives them a carbon footprint well below that of any other powered flying machine.

Operating costs depend on the job in hand and on its location but modelling done by the company on, for example, transporting people or goods to mines in remote parts of Northern Canada suggest that the Airlander comes out at about 10% of moving equivalent loads by helicopter and is a third of the cost of using cargo aircraft. Military surveillance costs are also an order of magnitude cheaper; a task that might cost £20,000 an hour or more using a helicopter would be closer to £2,000 to £3,000 per hour using Airlander.

Commentators have so often and for so long predicted the imminent revival of the airship as a serious contender in the transport market that further prophecy would be reckless. What can be said is that present circumstances – the emphasis on fuel economy and the advent of new technologies and materials – provide a setting more favourable to success than any for half a century. If HAV cannot make a commercial success of a craft such as Airlander, it is difficult to imagine who ever will.

THE 2016 ACCIDENT: HOW A WINCH FAILURE LED TO A HARD LANDING

Trying to test something the size of Airlander 10 in private is impossible, so it was in front of a clutch of camera lenses that Airlander's second test flight came to an undignified end on August 24 2016.

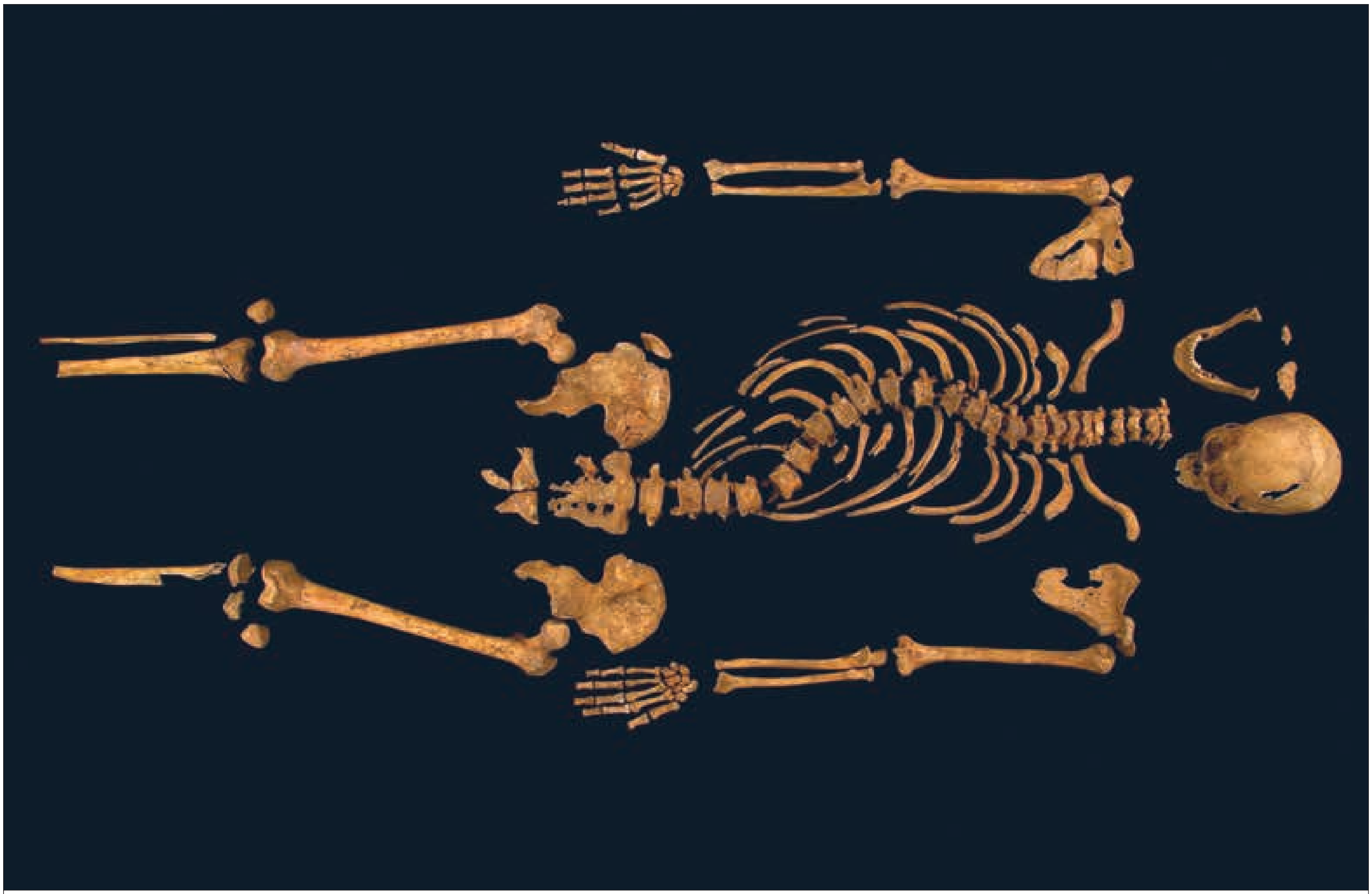
The culture of openness and safety that characterises the reporting and analysis of aircraft incidents applies equally to airships. A report by the Air Accident Investigations Branch, published at the beginning of March 2017, tells the story of Airlander's accident. The test flight lasted a little over 90 minutes and was successful. It approached its mooring mast and deployed the mooring cable. Ground staff attached this to the winch intended to complete the landing operation, but the winch failed to start. The pilot decided to make another circuit while it was fixed but the lack of any pre-arranged system for dealing with the mooring cable under these circumstances left it dangling from the front of the craft.

The pilot was told that the cable was roughly 50 feet in length. In fact, it was three times as long as that, and consequently snagged some overhead wires. To avoid further mishap, the pilot was obliged to make his second approach to the landing area at well above the prescribed height. This and other circumstances led to a steeper than intended angle of descent – and a hard landing.

BIOGRAPHY

Chris Daniels is Head of Partnerships and Communications at Hybrid Air Vehicles, and has been with the company for four years. He has a mathematics degree from the University of Oxford and an MBA from IESE Business School, Barcelona.

David Burns is Chief Test Pilot at Hybrid Air Vehicles. He has flown for Loganair, British Airways and Monarch Airways. David began flying airships with Airship Industries in the early 1980s and has worked with them and successor companies in testing, training and operations in many parts of the world.



The skeleton found buried at the site of the former Grey Friars Abbey in Leicester displayed signs of trauma and the effect of the scoliosis on the spine, a condition that is generally associated with the traditional depiction of Richard III © University of Leicester

SOLVING A HISTORICAL MYSTERY

Following defeat at the Battle of Bosworth Field in 1485, Richard III's body was lost for almost 530 years, until it was sensationally rediscovered beneath a Leicester car park in September 2012. Science and technology journalist Sarah Griffiths spoke to Professor Sarah Hainsworth FREng, Professor of Materials and Forensic Engineering at the University of Leicester, about how modern forensic engineering science helped to discover what happened on the battlefield.

Richard III remains one of Britain's most divisive and controversial monarchs. William Shakespeare painted him as a cruel hunchback, but in fact he promoted legal fairness by instigating a court for poor people, regulated weights and measures, and banned restrictions on printing and sale of books. He died valiantly leading his men in battle, and was the last English king to do so on home soil. Despite his reputation, the discovery of a skeleton with a distinctly curved spine in an unmarked grave in Leicester in what was once Grey Friars – a grand friary that was dissolved during the Reformation in 1538 – captured the public's imagination.

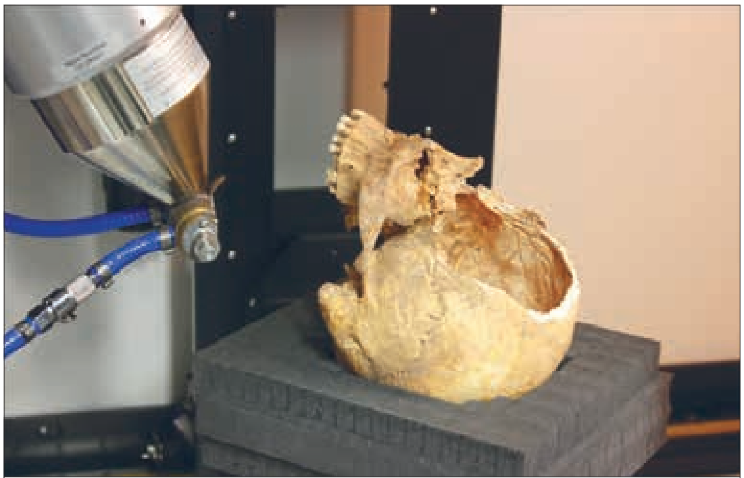
Led by the University of Leicester, the 2012 project to excavate the Grey Friars site, which is now partly covered by a Leicester City Council car park, was the first search for the grave of an anointed king. As luck would have it, remains that were suspected to be Richard III were revealed on the first day of the dig in August, in the first trench to be dug. Less than a week later, the completed skeleton was uncovered and the bones were removed and carbon dated almost immediately. DNA was extracted and compared to that of the king's descendants, and in February 2013 the remains were confirmed as Richard III.

THE ENGINEERING BEHIND THE DISCOVERY

The bones were imaged to allow anthropologists, pathologists and engineers to analyse the skeleton's injuries in greater detail. To shed some light on just how Richard III died, the investigation looked at the trauma to the skeleton using modern forensic techniques, including CT (computed tomography) and micro-CT scanning – 3D imaging on a small scale with increased resolution – in order to characterise the injuries.

CT scanning and doughnut-shaped 'CAT scanners' have been routinely used in medicine since the early 1970s. An X-ray source is located on one side of the ring with an X-ray detector on the other and the machine rotates around the patient to gather information from all angles. Sophisticated software is then used to turn the array of radiographs into a 3D image.

The complete skeleton was first laid out in an anatomical position, displaying considerable curvature of the spine, and underwent post-mortem CT scanning. The aim of the first CT scan was to create a 3D record of the bones that experts could work from, as well as the skeleton's spinal abnormality and the injuries upon the bones.



Each time a part of the skull was scanned, it generated 3,600 radiographs and this mass of data had to be reconstructed. As there was no quick fix for this challenge, selecting the most useful views took a great deal of care and time
© University of Leicester

The bones were then scanned using an Aquilion 64-slice scanner and the pelvis, spine and head were separately scanned once more to carefully gather important details that could help prove the identity of the remains. Bones that were identified as displaying injuries underwent high-resolution micro-computer X-ray tomography (micro-CT) imaging with a Nikon Metrology XTH 225 scanner and a PaxScan detector. This was one of the first times that micro-CT had been applied to analysing battle injuries on bone in an archaeological investigation.

Micro-CT is a much higher-resolution technique than conventional CT in which the X-ray source (an electron gun in a vacuum tube, not dissimilar to the cathode ray tube in an old television) and the detector remains static while the sample rotates. The resolution depends on the size of the pixel matrix employed and the spacing of volume elements or 'voxels', as well as the resolution of the detector, focal spot size, magnification, and how close the sample is to the X-ray emitter and the detector.

To improve the signal-to-noise ratio (which compares the level of a desired signal to background noise), the researchers chose to scan each bone of the skeleton for between six and eight hours, in order to give the highest possible resolutions. Micro-CT radiograph data was then reconstructed using proprietary Nikon Metrology software. This technique allowed the team to study the battle injuries in great detail.

One of the biggest challenges for the engineers was to avoid damaging the historically important skeleton while examining it. A polystyrene mould was used to hold the bones to ensure that they were securely mounted in the CT-scanner and could not move while the stage rotated.

Micro-CT images of the skull of Richard III. The image on the left shows the skull seen from the base. A is where the spine joins the skull and B and C are injuries that were likely to have been created with a short sword and halberd respectively. The image on the right shows a knife mark to the jaw, probably inflicted as the leather strap on Richard III's helmet was cut to allow his other injuries to be inflicted © University of Leicester

WHAT THE SCANS REVEALED

The CT scans were used to assess the structure of the rib ends and cranial sutures (a fibrous joint) among other features, to deduce that the man was 30 to 34 years old when he died. This discovery was consistent with accounts of Richard III, who was said to have been 32 years old when he fell in battle.

The experts found 11 injuries that had been inflicted at or near the time of death, as no evidence of healing was noted. Nine of the injuries were on the skull and clearly inflicted in battle, which hinted at the final moments leading to the king's death, as well as another two injuries to a rib and the pelvis. As no wounds overlapped, the team was not able to establish a specific order of injuries. However, it is believed that the most likely fatal injuries were two to the inferior cranium, which could have caused subarachnoid haemorrhage (injury to the brain) or an air embolus and killed the victim 'within a short time'.

The injuries on the skull are consistent with near-contemporary accounts of the battle, which suggest that Richard abandoned his horse after it became stuck in a mire and perished at the hands of his enemies. The number of cuts to the skull suggest a sustained attack. Interestingly, the location of the cuts as revealed by the CT-scan indicate that Richard III had lost his helmet, but a lack of defensive wounds to the arms and hands implies that he was still wearing other armour when he died.

As well as analysing the injuries, the university's forensic engineering expertise ('Forensics of knife crime', *Ingenia* 37) was used to identify the weapons that were potentially responsible for causing the injuries by analysing tool marks on the bones. One of the injuries, a puncture wound, was likely made by a rondel dagger that had a strong blade made for piercing; another would have appeared instantly more dramatic and was likely inflicted with a halberd, or axe blade, that cut through the skull and exposed the brain. Such a wound would likely be fatal, even today.

Upon closer inspection of the micro CT-scans, all 11 near-death injuries were found to be consistent with the types of weapons used in the late medieval period. For example, the researchers found a 10 millimetre v-shaped wound on the right side of the jaw. This was probably made by a dagger or knife, as the marks produced by swords typically have an uneven cross-section with one roughened wall and measure more than 20 millimetres. The team identified what weapons had likely been used to inflict the injuries by examining the striations, which are produced by marks present on the edge of a tool. These marks result from both the manufacture of the blade and damage that occurs during its use, meaning that the striations are unique to the tool that created them. This can make them difficult to identify; however, the engineers took macro-photographs of the striations to examine them closely and the use of micro-CT imagery to produce high-resolution images also helped. The team used a CT-processing software package called Osirex and an app called Bullit to produce the estimated wound tract on the pelvis, which demonstrated that of all the injuries, this was likely to have been inflicted post-mortem while the skeleton was over the back of a horse.

The team also used previous data from other medieval battlefields to identify the weapons, with help from Bob Woosnam-Savage, curator of European-edged weapons at the Royal Armouries in Leeds. They examined reports of battle injuries to skeletons that were involved in an earlier battle in the Wars of the Roses at Towton and also the Battle at Dornach in 1499. By comparison, Richard

It would be fascinating to compare the DNA of Richard III with the DNA of the two boys' skeletons that were found at the Tower of London and believed to be Richard's nephews

III appeared to suffer few injuries to the face. Medieval warfare was brutal and the skeletal remains often show considerable damage to the skulls.

A CLOSED CASE

The mystery of Richard III's death is now as resolved as it ever can be and the king's remains have now been formally laid to rest. Professor Hainsworth thinks that it would be fascinating to compare the DNA of Richard III with the DNA of the two boys' skeletons that were found at the Tower of London and believed to be Richard's nephews. However, the bones now rest in Westminster Abbey and it would require the permission of HM The Queen Elizabeth to access these.

In the future, working on other remains with battle injuries will allow experts to understand the different ways in which engineering and archaeology can combine and would like to solve other royal mysteries. For example, it could help decipher whether the last Anglo Saxon king of England, Harold Godwinson, really did die from an arrow thorough the eye at the Battle of Hastings in 1066, as depicted in the Bayeux Tapestry. The combination of history and forensic engineering science is fascinating because it brings the subject to life.

BIOGRAPHY

Professor Sarah Hainsworth FREng is Professor of Materials and Forensic Engineering at the University of Leicester. She has become the international engineering forensic expert on skeletal contact damage, uniquely establishing the sequence of injuries leading to the death of King Richard III.

RECREATING THE KING'S SKELETON AND GRAVE

After more than five centuries, Richard III was finally given a burial fit for a king in March 2015, when his remains were reinterred at Leicester Cathedral.

However, a year before the regal event, experts from Loughborough University's School of Mechanical and Manufacturing Engineering were invited to make a replica of the curiously-shaped skeleton, using 3D printing techniques. They created a 3D computer model from the CT scans of the remains, which were cleaned up using Materialise's Mimics Innovation Suite software. Laser sintering was then used to create a replica of the skeleton. This technique used a high-power laser to fuse small particles of plastic into realistic bones, building them up layer by layer. As the skull emerged from the powder of the laser-sintering machine, a number of the injuries on it were clear to see.

Researchers also made a 3D reconstruction of the king's original grave for posterity. During the 2012 dig, archaeologists made detailed drawings of the grave in which Richard III was, they think, hastily buried, and experts from the University of Leicester used laser scanning and digital photogrammetric techniques to create a detailed 3D reconstruction.

Researchers from the Leicester LiDAR Research Unit in the Department of Geology mapped the exact shape of the grave using a terrestrial laser scanner. They placed the instrument at different points around the grave from where it fired laser pulses in a 360-degree arc to record the length of time taken to bounce off a surface and return to the scanner.

The information gathered at each point combined to create a 20-million-point cloud of the site, which recorded the excavated grave walls and even soil textures. This data was then amalgamated with a survey using more than 80 digital photographs of the grave, shot from different angles, which were used to build a 3D model of the void beneath the now-famous car park.

The 3D interactive digital reconstruction of King Richard III's grave allows it to be explored from all angles. It can be viewed at sketchfab.com/leicester-archaeology

MACROBERT AWARD 2017

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 29 June 2017.

BIOLOGY-INSPIRED TECHNOLOGY TO FIGHT CYBERCRIME

DARKTRACE ENTERPRISE IMMUNE SYSTEM

Darktrace's Enterprise Immune System uses AI algorithms that mimic the human immune system to defend enterprise networks of all types and sizes.

Security software traditionally relies on reinforcing the perimeter of the computer network, in an attempt to stop cyber attackers from gaining access to internal systems. It is reliant on predefining what 'malicious' looks like, applying rules or signatures that identify known threats. However, insider and advanced threats have proven capable of overcoming the increasingly porous border because they are not predictable and blend into the background of day-to-day network activity.

Darktrace's Enterprise Immune System, developed by mathematicians and software engineers from the University of Cambridge, is a technology platform that uses unsupervised machine learning to defend organisations against advanced cyber-attacks from within computer networks, by identifying their emerging indicators.

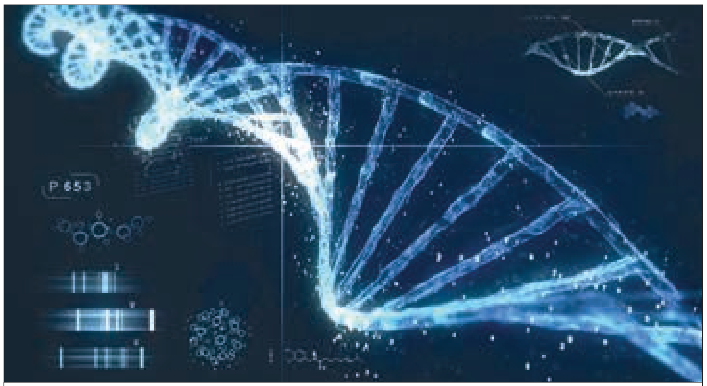
By applying unsupervised machine learning to the evolving challenge of cyber security, Darktrace has developed a new approach that addresses this problem in a more effective way.

INNOVATION

The Enterprise Immune System works on the principle that all networks are 'compromised' to some extent. The technology works by using unsupervised machine learning algorithms to form an understanding of what represents 'normal' activity for every user, device and network. Based on this evolving 'pattern of life' for an organisation, the AI algorithms can identify what is 'abnormal' and likely to be suspicious or threatening activity and can issue an automatic response akin to 'digital antibodies' to neutralise an attack that is in progress. The technology works in real time and continually refines its understanding of 'normal', which means that it recalibrates its assumptions in the light of organisational evolutions.

The ability to continually learn and update its understanding, based on evolving evidence, is key to the innovation. Machine learning can be hard to get working outside of labs in real-world, live data scenarios. While no two networks are alike, Darktrace overcomes the challenge of learning 'normal' for environments as diverse as industrial control systems, banking infrastructures and small businesses, without requiring configuration or manual tuning.

Similar to the human immune system, the principle of the Enterprise Immune System is to continually learn what is normal for its environment and detect early indicators of threats, before they escalate.



Darktrace's AI technology detects and neutralises emerging cyber-threats by issuing an automatic response akin to digital antibodies © Darktrace

BENEFITS TO SOCIETY

Cyber risk is at the top of the international agenda, as high-profile breaches raise fears that cyber-attacks and other security failures will endanger the global economy. Therefore, defending both organisations and individuals is important in order to safeguard enterprises, industries and jobs, as well as protecting critical infrastructure.

In addition to the threat of data loss, Darktrace can defend against attacks on the integrity of data. Amid political upheaval in many parts of the world and a loss of confidence in public authorities, Darktrace shines a light into complex environments and helps catch attacks in their nascent stages. In doing so, it can help restore the public's confidence in organisations as diverse as banks who manage their bank balances and healthcare providers that produce blood test results – systems that rely on data being scrupulously accurate.

COMMERCIAL SUCCESS

Darktrace has grown rapidly since its foundation in 2013. To date, the company's AI technology has been deployed over 2,400 times across 60 countries. Its customers include BT, the Church of England, Drax, Irwin Mitchell, and British Land. Its largest customer employs more than 100,000 people while the smallest employs less than 10.

The company's own employee head count has also increased steeply to accommodate demand for the product, doubling in the space of a year from 130 employees in January 2016 to more than 400 employees across 24 global locations.

For more information, please visit **www.darktrace.com**

BRITAIN'S MOST SUCCESSFUL POCKET-SIZED COMPUTER

RASPBERRY PI

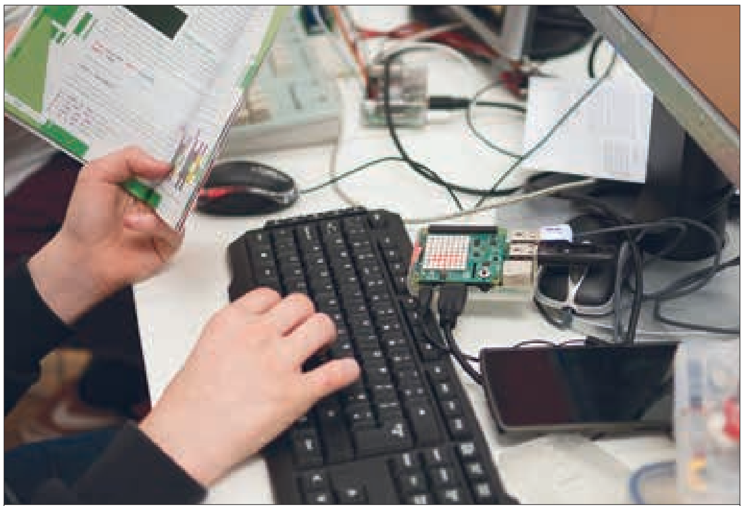
Raspberry Pi devices, and the Raspberry Pi Foundation, are helping more people learn about computing and digital making by providing opportunities for creative computing across the curriculum and beyond.

Around the turn of the millennium, university computer science courses began to see a dramatic decrease in the number of applicants. As personal computers and games consoles became more complex, fewer young people felt able to access the 'back room' workings of computers, reducing the number of hobbyists. At the same time, computer programming was not widely taught in schools.

Wanting to show future generations that computers could be used creatively, the Raspberry Pi Foundation began working on an innovation to promote programming education: low-cost, high-performance computers that people can use to learn, solve problems and have fun.

INNOVATION

The Raspberry Pi is a credit-card-sized microcomputer, comprising a 1.2 GHz (gigahertz) processor with graphics capability, audio and video output, and a USB port for generic peripherals such as a mouse and keyboard. The idea for the computer was developed by Eben Upton, a computing graduate from the University of Cambridge, while he was working for Broadcom – a major vendor of video and graphics chips for mobile phones. Upton realised that adding a conventional central processing unit (CPU) to the multimedia processor would transform it into a general-purpose computer. As the original design was developed for mobile phones, the board was credit-card sized, had low power consumption, and could be engineered for low cost and volume production.



A child makes pixel art using a Raspberry Pi and a Sense HAT add-on board. Events led by volunteers from Raspberry Pi's supportive community provide programming and digital making opportunities for thousands of people every year © Raspberry Pi Foundation

This system evolved into the Raspberry Pi, which went into production in 2011 and was successfully launched in February 2012. Twenty times more units were sold than expected and production had to be increased to meet demand.

Several models of the computer have been released since 2012, and all feature a Broadcom system-on-a-chip (SoC), which includes an ARM-compatible CPU and a graphics processing unit. The CPU gives access to the myriad of programming languages, device drivers and applications available in the Linux operating system's community, such as Scratch and Python. It is this system that allows people to experiment.

BENEFIT TO SOCIETY

The Raspberry Pi Foundation is a charitable organisation and all of the profits generated from sales of Raspberry Pi devices are used to fund its outreach and education activities. These include Code Club, a worldwide network of over 10,000 after-school computing clubs for children aged between nine and 11, which is soon to expand to support ages up to 13, and Picademy, a two-day intensive teacher training programme that has reached over 1,000 teachers and 100,000 students since 2014.

By providing a cheap general-purpose computing platform, preloaded with programming software and accompanied by high-quality educational resources, Raspberry Pi has lowered the barriers to entry for young people interested in pursuing a career in engineering and helped inspire young people to take an interest in computing. Since 2012, there has been a dramatic recovery in the number of applicants to university computer science courses, which can be attributed in part to the efforts of Raspberry Pi and its partner organisations.

COMMERCIAL SUCCESS

The computer was initially developed for the education community, but its audience has grown to include hobbyists, as well as being used in industrial and commercial applications, from creating video games to robots, multi-room sound systems, pet feeders, or even science experiments. The flagship model costs $35, with a simpler model at just $5, and more than 12 million have been sold across the world since its launch – making it the most successful British computer ever.

For more information, please visit **www.raspberrypi.org**

MARKET-LEADING SURFACE-GUIDED RADIATION THERAPY

VISION RT

Vision RT's AlignRT system tracks a patient's position before and during radiotherapy to maximise comfort and treatment accuracy, and can even reduce the need for permanent tattoos on patients.

More than one in three people will have cancer at some point in their lives, and around half of them will require radiation therapy, which often successfully cures patients.

Radiotherapy works by destroying cancer cells using high-energy photon beams, but these beams can also be harmful to healthy tissue. Therefore, healthcare professionals do their utmost to ensure that only the target area receives the radiation dose. However, slight movements that patients naturally make during treatment are almost impossible to detect, and these can lead to radiation damage to healthy tissue and potential long-term health problems. Historically, patient position during treatment was monitored by treatment staff via closed-circuit television, but this method is unable to pick up such small movements.

In a bid to make sure that radiotherapy is delivered as accurately as possible, Vision RT developed AlignRT, a completely non-contact system that continuously tracks the patient's position in 3D before and during treatment with sub-millimetric (better than one millimetre) accuracy.

INNOVATION

Three AlignRT stereoscopic camera units are ceiling-mounted in the radiotherapy treatment room. They project a pseudorandom pattern onto the surface area of the patient's body, which is picked up by the cameras and used by software to reconstruct a 3D model of the surface area in real time. This is then compared to a 3D surface reference model, from a previous X-ray or CT (computed tomography) scan, to determine any movement from the patient's ideal position.

This real-time 3D mapping of the surface gives directions so that the patient can be positioned faster and more accurately. During treatment, the AlignRT system senses movement from the patient, caused by breathing for example, and automatically pauses radiation delivery, preventing damage to healthy tissue.

BENEFIT TO SOCIETY

The AlignRT system helps improve the speed of treatment, ensure the accuracy of radiation delivery and enhance patient comfort. Without surface-guided radiation therapy, permanent tattoo reference points on the patient are usually required to mark the correct position for treatment, and these remain a permanent reminder for patients of their cancer. Now, centres can reduce or even eliminate the use of tattoos.

AlignRT also enables an effective 'breath-hold' treatment for breast cancer. Damage to the heart is a serious potential complication for breast cancer radiotherapy patients, because of the left breast's proximity to the heart. AlignRT can monitor when a patient takes a deep breath, which moves the heart away from the chest wall, and thereby ensures that the radiation is only delivered to the breast, and not the heart, while the patient holds their breath. A recent clinical study showed that 0% of patients who were treated with the guidance of AlignRT experienced damage to heart blood supply, in comparison to 27% in a previous study using traditional techniques.

Ceiling-mounted AlignRT camera units map the surface of a patient's body to ensure that radiotherapy beams are correctly delivered and paused if the patient makes any slight movement © Vision RT

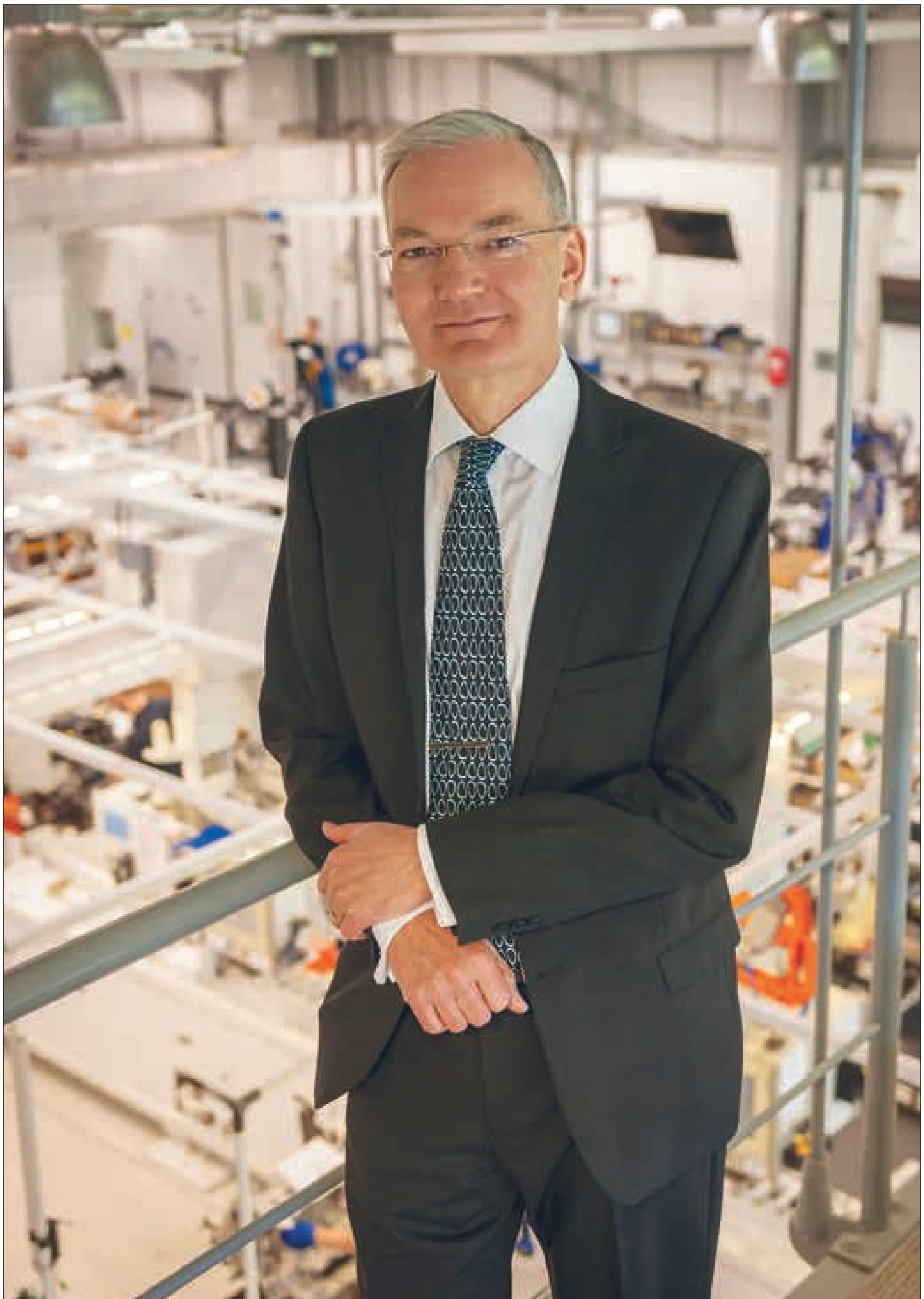
COMMERCIAL SUCCESS

Vision RT was founded in 2001 in an attic in north London, and is now the market leader in surface-guided radiation therapy, with nearly 1,000 systems in use across the world, including multiple units within the NHS. The company is profitable, having experienced growth of 260% between 2013 and 2015. In 2016, it was awarded two Queen's Awards for Enterprise – one for international trade and its overseas sales growth, and one for innovation. Vision RT employs around 140 people and is continuing to expand its operation as the clinical use of its products and its revenues increase.

The technology is used in many cancer centres around the world (including all of the top five cancer centres in the USA) for a wide range of cancers, including breast, brain and lung, and its clinical value has been evidenced in more than 60 peer-reviewed papers.

For more information, please visit **www.visionrt.com**

THINKING ABOUT THE REVOLUTIONS



Professor Neville Jackson FREng joined Ricardo following his graduation from Imperial College London and has been at the company for more than 30 years © Ricardo

An interest in engines first drew Professor Neville Jackson FREng into engineering and, over the years, his work has covered almost everything related to transport. As Chief Technology and Innovation Officer at Ricardo, part of his role is to think about the future for car manufacturers, from cleaner diesels to autonomy, as well as trains and the software that controls them all. He talks to Michael Kenward OBE about the engineering challenges of modern mobility.

Professor Jackson found a job with Ricardo that really fuelled his passion for engines. Established in 1915 as an engines business (and now a global engineering manufacturer and consultancy), Ricardo was a natural home

Studying for an A level in design technology convinced Professor Neville Jackson FREng that he wanted a career in engineering. He had to design and build his own twin-cylinder steam engine, making his own parts, including the crankshaft and a rotary valve he had also designed himself, and this experience prompted him to study mechanical engineering at Imperial College London. "I had really got interested in engines of all types," he says. "Especially motorcycles." After his first few years studying mechanical engineering, Professor Jackson's degree sponsor Marconi could not guarantee to offer him a full-time position after his final year and suggested that he look elsewhere. He found a job with Ricardo that really fuelled his passion for engines. Established in 1915 as an engines business (and now a global multi-industry consultancy and manufacturer of high-performance products), Ricardo was a natural home for Professor Jackson.

When Professor Jackson joined Ricardo as a development engineer in 1982, working on thermal measurement techniques, the company was still very much an engines operation. Today, engines account for about half of the business says Professor Jackson, now the company's Chief Technology and Innovation Officer (CTIO). But he explains that, over the years, the company has moved into other areas of automotive engineering. "The first thing that we did was move into complete powertrains, which included transmissions and drivelines. Then came vehicle engineering, and making powertrain systems work in an optimal manner within vehicles." The engines business is just one of Ricardo's 10 or so businesses, which include work on railways, energy and the environment, and more recently, the broader domain of mobility.

Professor Jackson now spends some of his time anticipating where the transport industry, especially the automotive sector, might be in 20 years' time. This is, he explains, an important part of his role as CTIO. "My job is to understand what is going on outside our business that will affect us in the future: which really important future technologies are going to have an impact on us? What kind of things can we learn from outside our sectors that could make us a better business?" This emphasis explains why Professor Jackson estimates that he spends 30% to 40% of his time looking at the outside world, studying what is happening in universities and sectors that Ricardo's core businesses might not typically talk to.

INDUSTRY RESEARCH

Another of Professor Jackson's roles as CTIO is to lead the company's R&D strategy and develop the future R&D landscape. Ricardo invests around £10 million a year in research, which includes a significant contribution from research grants via the EU Framework programme and various other government agencies. The company's corporate R&D division, Ricardo Innovations, delivers research for the whole group while also exploring new technologies that could lead to new business streams. One of Professor Jackson's key responsibilities is to ensure that the company gets a good return on its investment. "We're always looking at how we can maximise returns from the investment that we make in R&D," he explains. "We put a lot of effort into measuring impact." As you would expect of engineers, Ricardo maintains a detailed record of its R&D spending. "We have comprehensive data going back 15 years," he adds, "so we know what makes a good investment and what does not."

Research is so important to Ricardo's activities that you could almost see it as an R&D arm for the whole industry. "We would like to think that," says Professor Jackson. "Our business is R&D. We are an R&D service to our customers." He admits that, when it comes to investing in research, the company's timing isn't always perfect. "One of our biggest challenges is often being too early," he explains. "We will invest in things, spend quite a lot of money, but the customers have not really got to the stage of outsourcing that kind of work yet." Take advanced driver assistance systems and 'onboard vehicle functionality', for example. "We put a lot of effort into that whole area more than 10 years ago and it has taken a long time for that market to develop." Now, of course, hardly a day goes by without a carmaker, or even an electronics business, touting its latest venture into autonomous vehicles.

Professor Jackson's take on autonomous vehicles is that the first widespread application of the technology could be in 'platooning' of heavy goods vehicles: 'trains' of automated vehicles that travel three or four metres apart, with trucks braking and accelerating under the guidance of the lead vehicle. Ricardo first worked on platooning about eight years ago. Professor Jackson sees two significant advantages to platooning: vehicle efficiency and the working hours of drivers. "Running the vehicles together could lead to a significant aerodynamic benefit, and running four or five vehicles together could save between 10% and 15% on fuel

Professor Jackson believes that platooning, where automated heavy goods vehicles follow each other under the guidance of the lead vehicle, could make this form of transportation more energy efficient and transform drivers' working hours © Ricardo

consumption." Current law says that drivers can spend only so many hours behind the wheel. "If the drivers in following vehicles could get a rest credit because they are not driving, when they have finished platooning across Europe they might not have to take a rest break when they have got to peel off and follow their own routes." This would not only cut costs for truck operators; it could also be a solution to a potential shortage of drivers. "There are concerns about the lack of drivers for trucks, particularly in the US, and some level of autonomy could help to alleviate that."

"What is impressive," adds Professor Jackson, "is to see the whole road train with three or four metres between each vehicle doing an emergency stop. There is one vehicle that is always going to be the worst at slowing down. The rest are modulating their braking to maintain the gap. It is really interesting to watch how the control systems make that work." Ricardo recently played its part in ensuring the safety of truck platoons as a part of the EU's EcoTwin project, which gathered together specific knowledge and experience from a consortium of European organisations to automate two trucks to drive closely behind each other. When advising on the safety of autonomous vehicles, the company drew on its experience in rail systems and their safety assurance processes.

SECURE SYSTEMS

Rail is an important part of Professor Jackson's domain that has grown considerably over the years. When he joined Ricardo, the company employed around 400 people; these days it employs a team of over 450 rail engineers and specialists alone, with 200 of those employed in Utrecht in the Netherlands. The company is a certified independent authority in the rail industry, which means that it ensures that companies operate robust safety and security assessments. "You need independent assurance of a system before you can operate it," explains Professor Jackson. This is what led to Ricardo taking its knowledge of safety requirements for driverless systems from the rail industry and applying it to autonomous vehicles.

Professor Jackson sees software security as a growing subject for the automotive industry. "At the moment, a premium vehicle could have up to 100 million lines of code in it. Only a very tiny part of that is safety critical, while most of it is in the 'infotainment' system. Increasingly, as we go towards advanced driver assistance and autonomous systems, more and more of that software will become safety critical."

Even before autonomous vehicles can take over complete control, there will be increasing software-controlled 'driver assistance' in cars. At the moment, it may just be the car's throttle that is controlled through a 'drive-by-wire' electronic link rather than a physical connection. Before long, Professor Jackson predicts that it will be brake-by-wire, followed by steering and other controls. "Ultimately, you want to stop the driver from doing stupid things," he explains. "How can you stop them from crashing into the vehicle in front or rolling the car over? How do you ensure that when they brake they can still steer? Then, looking at the steering, did you really want to change lanes there?" Any 'by wire' control relies on safety critical software that has to be checked for coding errors.

KEY INFRASTRUCTURE

Thinking about how the electronics in a vehicle will change is another area where Professor Jackson's role extends beyond his work within Ricardo. He has led the development of a long-term technology 'roadmap' for the 'future electrical and electronic architectures' for vehicles for the UK Automotive Council. He has also been responsible for producing roadmaps on fuels and energy, heavy duty and commercial vehicles, the internal combustion engine and virtual product engineering, which have now become the key strategy documents for the UK Advanced Propulsion Centre – an organisation that was created by the auto industry, and jointly funded with the government, to support technology commercialisation. Professor Jackson draws on this work to support his take on the future of motoring. It may take some time for fully autonomous cars to be viable and certified safe and become accepted by motorists, but there are fewer obstacles to the take up of electric vehicles, especially as prices come down. "The costs of the battery for electric vehicles will probably cease to be a critical issue by 2030," he predicts. But that is not the challenge: he wonders how the electricity distribution infrastructure can be upgraded to recharge the ever-larger battery packs fitted to vehicles.

Professor Jackson sees the local power network as the real challenge: plug in every car parked on a suburban road and "the whole thing will fall apart. It will blow the substation." Average maximum power demand for UK dwellings is between 7 kW and 8 kW (kilowatts), with a peak hourly load of around 2 kW with domestic electric heating and 1 kW without. This will be at least doubled with electric vehicle charging. "As batteries become bigger, it will take more than a day to recharge an 80 kWh battery by plugging into a 3 kW supply. Larger batteries will need 7 kW or 14 kW recharging facilities to be practical, but there is currently not the capacity to do it." Who is going to pay to bring that capacity to those urban streets? Professor Jackson asks. "Ricardo's energy environment group has extensively explored this whole issue of changing the way that the grid is operated to get as much use of existing capacities as possible."

This leads Professor Jackson on to thinking about how much we use our cars. As he says, "95% of the time, your vehicle is sitting on the road doing nothing. It is such a waste of resources and capital. If you could increase that usage from 5% to 30%, the cost per mile goes down dramatically in terms of capital cost. You can make the whole mobility system so much cheaper."

Professor Jackson doesn't talk so much about cars as about mobility. Another big area for him is 'smart cities', an area that he agrees is "a little bit hyped" but it does encourage wider thinking. "Mobility is not just about the vehicles; it is about the infrastructure, and the communications and energy systems required by the city. It is also the logistics. How do we move people and goods around efficiently and at the right time? How do we achieve this without causing congestion and what kind of vehicles do we need?"

AN ENGINEER OF AI

Recently, Professor Jackson has also put a lot of time into another overarching aspect of the automotive industry, the application of machine learning and artificial intelligence (AI) to product design, validation and manufacturing. He explains the issue with his own set of questions. "How do I speed up the computer-aided engineering process and do less testing? How can I learn from all of the data that I have on all of my past products – and all of its in-service characteristics – so that I can make better decisions in the design process? What can happen if I use machine learning and AI to optimise design?"

Professor Jackson's personal view is that current demonisation of diesel is a blip. "Diesel is used because it has lower CO_2 emissions, the engines have been cleaned up with particulate traps and huge strides have been made in particulate levels where, quite frankly, a diesel is better than gasoline. However, in doing that we have introduced a problem with nitrogen dioxide, which is poisonous." © Ricardo

He urges all engineers to pay more attention to the opportunities of exploiting AI. His message is to not leave it to the financial and pharmaceutical industries to make all the running. "I have put a lot of time into that in the last couple of years, working out what it means for us as a business. Thinking seriously about what AI can do for engineering, especially product design, development and manufacturing." Again, he throws questions out for his fellow engineers to consider. "How can we optimise our manufacturing operations right from the early stages of design? How do you join up the whole engineering process under a virtual connected system?"

There is, Professor Jackson admits, something of a data challenge in engineering, which may explain why it is harder to deploy AI. "Within an engineering context, many of us have vast amounts of digital data but digging into that and reusing it is really labour-intensive." He sums up the issue through three laws of data processing. "There is Moore's law [in its broader sense that overall processing power for computers will double every two years], which we all understand," he explains. "There is another law that says that the amount of data produced increases exponentially according to the number of connected systems you have. Then there is the law that says that the amount of data produced grows much faster than your ability to analyse it. AI can help with all that data. Knowing what to do with, and what is in, really big data is one of the issues of engineering data. A good example for engineering data is the definitions for rows and columns of seemingly random numbers – what units do they use? The idea behind the AI systems is that if you are intelligent enough you can work it out."

CLEANER ENGINES

For all his thinking about the future and the bigger picture of transport, or mobility, Professor Jackson has not abandoned today's problems. He still has to think about the engines that attracted him to engineering and Ricardo. For example, diesel engines have witnessed an amazing about-turn. Until very recently, they were sold as motoring's solution to climate change; in the short-term at least, the diesel engine is now painted as the primary cause for poor air quality in cities and an overnight disaster. Poorly designed emissions regulations restricted the need for emissions control to a specific driving pattern, which led to much larger emissions of nitrogen oxides (NOx) in real-world operation.

Professor Jackson's view is that the illegal cheating in emissions tests exposed in the US was a one-off and that the industry can deal with NOx, albeit at a price. The problem with diesel emissions is "nothing new," says Professor Jackson, who reviewed nearly a century's work on controlling emissions when he worked on a presentation for the Royal Academy of Engineering's *View from the top* event in 2015, entitled *Future mobility, energy and resources – a perspective formed from 100 years of innovation*. "There was a stage where there was such a problem with buses' diesel emissions that bus drivers were liable to be stopped by a policeman and sent back to the depot if there was too much smoke." The answer, he adds was to gradually refine and get better. In recent years, diesel emissions have been reduced, although he insists that there is still room for more refinements.

However, engineering has not reached the end of the road. By 2020, Professor Jackson predicts that diesels will be as clean or cleaner than their gasoline counterparts. "The downside is that they will get more expensive because of the cost of after treatment and emission exhaust control." His assessment is that the extra cost of cleaner diesel engines, in addition to the existing cost premium over gasoline engines, could be between £500 and £1,000.

There are plenty of reasons for Professor Jackson to keep an eye on advances in diesel engineering as well as the wider issue of mobility. It is an important part of his position as an expert on the future of automobiles in a low-carbon world and mobility, a concept that goes beyond transport. As well as keeping a close eye on the energy business, Professor Jackson keeps an eye on the bigger picture. That stretches into thinking about such subjects as total environmental impact of future policies and products, such as the need for what he dubs as scarce resources. "Whether that's magnetic materials, or battery materials, or in the future, maybe even water, those are going to be increasing challenges."

This activity inevitably takes Professor Jackson into working for governments. "We do quite a lot of work on policy, supporting governments, cities and public authorities to advise them on transport solutions and how they can select the right kind of vehicles for their specific operations." This outward-facing remit also includes Professor Jackson's roles on industry bodies and in policymaking circles in Brussels and the USA, for example. "I will try and work with policymakers to understand what direction they are trying to go in, and then how it relates to the automotive industry, the energy industry, or the rail industry in general." Today, then, Professor Jackson has a much wider view of the engines of change.

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, **1959**. Awarded a bachelor's degree in mechanical engineering, **1982**. Development engineer in Ricardo's gasoline research department, **1982–1984**. Various roles in Ricardo's diesel research department, **1984–1992**. Manager, powertrain and vehicle research department, Ricardo, **1992–1995**. Senior manager, engine engineering, Ricardo, **1995–1998**. Chief Engineer – technology, Ricardo, **1998–2000**. Product Group Director, technology, control and electronics, Ricardo, **2004–2005**. Global Product Group Director – advanced technology, Ricardo, **2000–2010**. Group Technology Director, Ricardo, **2006–2010**. Visiting Professor, University of Brighton, **2006–present**. Fellow, Institution of Mechanical Engineers, **2009**. Chief Technology and Innovation Officer, Ricardo, **2010–present**. Fellow of the Royal Academy of Engineering, **2011**. Vice Chairman, European Road Transport Research Advisory Council, **2011–present**.

INNOVATION WATCH

FARMING STRAIGHT UP

Hydroponics, growing plants without soil in nutrient-enriched water, is a technique that has been used in some form for centuries. The approach has gained popularity over the last decade or so and has been used to grow various crops across the world. As the global population grows and food security is threatened, its faster growth and larger yields have become increasingly important.

Suffolk manufacturer Aponic, led by former aviation engineer Jason Hawkins-Row, has developed a food-growing system based on the same principles as hydroponics. Its method allows plants to be grown in vertical columns with the roots in air, which is more efficient and sustainable than using water.

Jason's interest in natural eco-systems began when he became involved in projects that looked at natural methods of rainwater recycling and water purification. The inspiration for the growing system came when his fruit and vegetables were stolen from his allotment, which encouraged him to ensure that his food was grown securely.

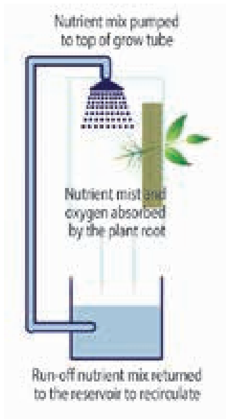
The company's aeroponic system holds plants by the roots inside vertical growing tubes filled with air. Every 20 minutes, a mixture of water and nutrients is automatically sprayed onto the roots for 10 to 15 seconds. The overall spraying time for the plants totals just 18 minutes each day. As it uses so little power, the system can be run 'off grid' by electricity generated by solar or wind, meaning it can easily be used in developing countries or in places with an unreliable energy supply.

Aponic's vertical growing system allows 12 plants to be grown in the same space that one plant would use in soil

The nutrient and water mix is recycled through the tubes and fully used in the growing process, which reduces water usage by an average of 90% compared to traditional growing methods. Aeroponic systems have even been used by NASA, as they can successfully produce food in both zero and artificial gravity environments.

This type of 'vertical farming' allows crops to be produced on smaller land area: 12 or more plants can be grown in the same space it would take to grow one plant in soil. Systems can be placed in greenhouses, barns and outbuildings, and vertical farming is popular in urban areas, such as industrial units and abandoned buildings.

Planting, tending and harvesting are easier for operators, who can work comfortably in a standing position. Removing soil from the equation means that there are no slugs, soil pathogens or weeds, reducing the cost further by removing the need for weed-killers. The pH of the water that the plants receive can be controlled, and the nutrients can be carefully adapted to the different stages of growth, so that growing conditions are optimal. If the system is used indoors, then temperature, humidity and light can be controlled, and matched with a nutrient regime and CO_2 injection regardless of season, environmental conditions or geographical location. This has implications for seasonal crops, and means that commercial farmers can consistently produce perfect crops to a reliable timescale.



In Aponic's system, nutrients are sprayed directly onto the roots of plants. Excess water and nutrients are recaptured and recycled

As part of the NIAB (National Institute of Agricultural Botany) Innovation Hub, Aponic is developing collaborative relationships with universities and research facilities to deliver the growing systems and training in developing countries where there are problems such as limited infrastructure, water shortages or bad soil.

As the UK currently imports 48% of its fresh food, Aponic hopes to reduce the need for imports and increase sustainable food security. It has recently developed modularised freight units to be stacked in barns or installed in growing containers to produce low-input, high-value output modular farms that are being sent all over the world. It is also working with large tech companies to develop a remote control and monitoring system to develop completely traceable produce.

For further information, visit **www.aponic.co.uk**

HOW DOES THAT WORK?

SPECTRUM

Radio spectrum is the part of the electromagnetic spectrum, a continuous range of wavelengths, that is widely used in modern technology. Particularly used in telecommunication, interest in the radio waves is expected to increase as 5G is rolled out and mobile communication is used more and more.

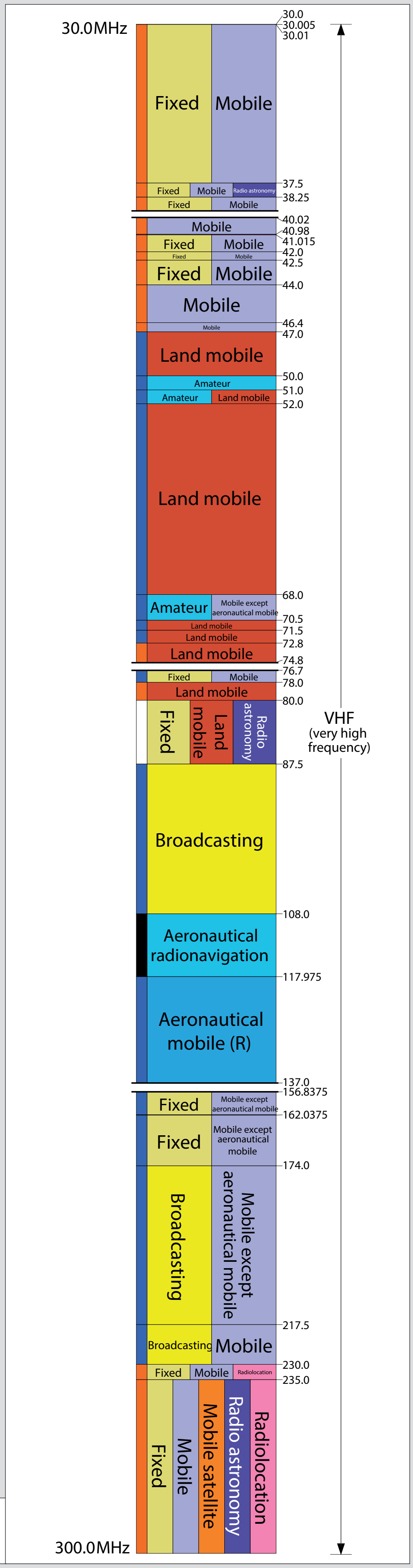
For something that is regularly auctioned for billions of pounds, radio spectrum is surprisingly difficult to describe. The term 'radio spectrum' typically refers to the part of the electromagnetic band that is used for radio communications, often taken to be 30 kHz to 300 GHz. Anything above these frequencies is light, UV and other bands.

The radio spectrum is conventionally divided into bands by international regulatory bodies such as the International Telecommunications Union (ITU), a branch of the United Nations. These bands are then sometimes allocated to particular uses. So, for example, the '800 MHz band' spans 790 MHz to 862 MHz in Europe and has been allocated to mobile communications, so is used by mobile operators to deliver 4G services. Almost every part of the spectrum has been allocated to at least one service, although some is set aside for anyone to use, such as for Wi-Fi and Bluetooth solutions.

More specifically, when someone such as a mobile operator buys a spectrum licence, they buy the rights to use a particular band of frequencies for a specified period of time, often 15 to 20 years. The government promises to enforce this by prosecuting anyone else who tries to use the frequencies. In that respect, there are analogies to buying a leasehold on a piece of land. Just like land, the value of spectrum varies according to its quality and the uses it can be put to. There are issues with noise generated by neighbours, detailed questions around where the boundaries actually lie, concerns over whether one proprietor owns too much and is therefore dominant, and more.

It has been said of land that 'they just don't make it any more' and the same is true of spectrum. There is continuous pressure to use it ever more intensively and that has led to recent trends to find intelligent ways to share it and to pressure those hoarding it to return or sell it on. Its value is huge; without the ability to use spectrum with certainty, it would be difficult to invest in mobile networks, air-traffic control systems, TV and radio transmission, satellite communications systems and much more. Various studies have estimated that the use of radio spectrum adds about 3% to a country's GDP but it is hard to envisage how a modern democracy could function without well-managed yet efficient use of the radio spectrum. In the UK, management of spectrum is assigned to Ofcom, which determines usage, decides who gets to own it and polices interference.

Interest in radio spectrum is expected to grow as 5G moves closer to being deployed and demand continues to increase at an unprecedented pace as more mobile services are consumed.



The frequency allocation chart for radio spectrum. This has been adapted with permission from part of Roke's *Spectrum management and frequency allocation* chart. A full version can be downloaded at www.roke.co.uk/media/roke-hub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INSPIRED WORK

London's Science Museum wanted an engaging space, founded in the best design and technology, to explore how mathematicians have shaped the modern world.

Arup provided engineering and lighting design for Mathematics: The Winton Gallery, working in collaboration with the designer Zaha Hadid Architects.

The curved overhead structure represents airflow around the Handley Page aircraft suspended at the galleries centre. The lighting scheme follows the aerodynamic field of the plane to bring a complex mathematical concept to life.

Image: Giulio | Arup ©

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