ingenia

DECEMBER 2017 ISSUE 73

DIGITAL IMAGE INVENTORS
SLENDER SKYSCRAPERS
MEDICAL TECHNOLOGY
SLIDING BRIDGE
BLOODHOUND

ROYAL ACADEMY OF ENGINEERING

www.ingenia.org.uk

ROYAL ACADEMY OF ENGINEERING

Sponsors

The Royal Academy of Engineering acknowledges the generous support of the following organisations for *Ingenia*:
- Arup
- BAE Systems
- Rolls-Royce plc

Published by the Royal Academy of Engineering
Royal Academy of Engineering,
Prince Philip House, 3 Carlton House Terrace, London SW1Y 5DG
Tel: 020 7766 0600 Website: www.raeng.org.uk Email: editor@ingenia.org.uk

Registered charity no. 293074

Editor-in-Chief
Dr Scott Steedman CBE FREng

Managing Editor
Gemma Hummerston

Editorial Assistant
Portia Sale

Associate Director, Communications and Partnerships
Jo Trigg

With thanks to
Beverley Parkin

Ingenia welcomes proposals and suggestions for articles that aim to stimulate readers from both within and outside the engineering community. The writing style should be clear, authoritative and easy for non-specialists to digest. Prospective authors should submit a one-page outline to the Managing Editor, the Editor-in-Chief or to any member of the Editorial Board.

Ingenia online can be found at **www.ingenia.org.uk**

Design
The Design Unit www.thedesignunit.com

Print
Manor Printing Services www.manorprinting.co.uk

Ingenia magazine is recyclable. The cover is treated with a recyclable laminate, the inks are vegetable oil based and the paper produced under Forest Stewardship Council guidelines.

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

Front cover
A computer-generated image of the Bloodhound in the desert © Flock London

ISSN 1472-9768

Royal Academy of Engineering promotes excellence in the science, art and practice of engineering.

Ready to break records p12

Copenhagen's 'kissing' bridge p18

How I got here p8

Accurate targeting of tumours p28

The sky's the limit p33

A talent for bursting bubbles p38

CONTENTS

@RAEngNews #IngeniaMag

This QR code links to www.ingenia.org.uk containing a searchable archive of all *Ingenia* articles

EDITORIAL

OPEN DATA OPPORTUNITIES

Dr Scott Steedman

It is no exaggeration to say that the 21st century is well on the way to becoming the data century, as the ability to capture and process data opens up many opportunities, including the possibility of creating whole new industries. The raw material for this potential revolution is freely available, with a whole new 'open data' movement showing just what is possible. However, as yet there is little evidence that the engineering sector is aware of the possibilities of open data.

The Open Data Institute (ODI) defines open data as data that anyone can access, use or share. Hundreds of companies in the UK already use data published on the internet by government and public agencies to offer new insights into everything from travel to recruitment. Transport for London (TfL) and the Ordnance Survey are two of the most celebrated providers of data, which has fuelled the creation of dozens of popular apps, particularly in relation to travel planning and geo-location.

Beyond tools that help navigate the vagaries of London's transport network or access public information more efficiently, open data has had limited impact on traditional industries in the engineering sector. When it comes to investing in physical infrastructure, production lines or software systems, there remains a persistent problem of trust in the reliability of the open data. How can engineers assure the quality of the data they use if there is no contract with the provider?

In 2015, a joint report from the Royal Academy of Engineering and Institution of Engineering and Technology, *Connecting data: driving productivity and innovation*, recognised the importance of open data as a driver of innovation. It called on every industry sector to consider what data it holds and in what circumstances it can be released, saying that much potentially valuable data remains locked away in corporate silos or within sectors.

Open data provides two major opportunities for innovation. The first is speed to discovery, joining the dots that already exist to create the next breakthrough in understanding. Academic research depends on painstaking efforts to gather the data across multiple sources. This takes time and requires a vast effort, with all the associated risks of error, misinterpretation or oversight. What if all publicly funded research data (once the original research team has secured intellectual property) was openly published in a standard format? How much faster could other researchers (or computers) mine the data and make their own new discoveries?

The second, more challenging, opportunity is where the innovation relies on a future stream of data from another source. It could be weather information, product specifications, traffic data, corporate statistics, even social media. Will the data stream be there next year? Can it be trusted? The question of how to assure the sustainability of open data is the next great challenge for the open data movement.

In June, the Royal Society and the British Academy recommended the creation of a new independent data stewardship body that would oversee the management and usage of data. Their report, *Data management and use: Governance in the 21st century*, says that agreeing high-level principles on the use of data is critical to giving innovators the confidence to explore new technologies.

In October, Innovate UK announced new funding of £6 million over three years for the ODI to continue its work to keep the UK at the forefront of data use to drive new and improved products and services, through a series of research and development projects aimed at unlocking the potential of open data to transform industry. Helping businesses to understand emerging data technology is central to the ODI's work.

Securing a breakthrough in the engineering sector's use of open data will require new thinking on the relationship between provider and user. Those that hold data need to be convinced that sharing it will bring greater long-term value than holding on to it. Innovators, consumers and regulators need to agree standards that set out best practice and avoid regulation as far as possible. Once it is clear that open data benefits providers as well as users, then there is a incentive to maintain the quality and reliability of the data over time. Only then will the real opportunities become clear in the traditional engineering industries.

Dr Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

AWARD-WINNING YOUNG TECH ENTREPRENEURS

Ryan Yasin's Petit Pli clothing range employs the Negative Poisson's ratio so that garments can expand as the child grows

Three young engineers have been awarded prizes for entrepreneurial innovations in the worlds of fashion and business.

Ryan Yasin, a 24-year-old graduate of Imperial College London and the Royal Academy of Art, won the James Dyson UK Award for innovation in September for his children's clothing range that grows with the child. Frustrated by how quickly his baby nephew outgrew the outfits that he bought him, and aware of the financial and clothing waste inherent in the garment industry, Ryan invented Petit Pli clothing that can comfortably fit a child from six to 36 months. The Negative Poisson's ratio, which allows materials to expand in two directions at the same time, is key to the garments' expansion. Ryan integrated the ratio's properties by using pleated structures that have been heat treated to ensure permanence. This resulted in clothes that expand bi-directionally, are wind- and waterproof, and can be folded down small enough to fit in a pocket.

Ryan was given £2,000 to develop his idea and entered into the running for the international James Dyson Award, which will give the winning contestant £30,000 to develop their idea.

Later in September, the Royal Academy of Engineering's Enterprise Hub hosted the final of its Launchpad Competition, which is aimed at promising young technology entrepreneurs in the UK, aged 16 to 25.

The winner of the competition was 25-year-old Nick Schweitzer, who has invented a machine-learning tool to help brands uncover future ideas. He received the JC Gammon Award, a £15,000 prize, and membership of the Enterprise Hub, which includes the benefit of mentoring from Academy Fellows.

Nick has created a web-tracking and machine-learning technology that uses the internet to offer novel solutions to business problems. It identifies the future direction of an industry to help business innovation succeed where it is currently failing. The current methods used by agencies to identify client problems and solutions – ranging from desk research to face-to-face interviews – can be slow and prone to error.

A separate People's Choice Award was presented following an audience vote and online voting in the run-up to the event. It was won by Brittany Harris for her technology Qualis Flow, a remote sensing and data management tool to help users manage their resources more sustainably. Brittany will receive £1,000 and membership of the Enterprise Hub.

More information about the Launchpad Competition and Enterprise Hub can be found at **enterprisehub.raeng.org.uk**

(L–R) People's Choice Award winner Brittany Harris, Launchpad Competition winner Nick Schweitzer and fellow finalist Jack Pearson of EngX

ENGINEERS CELEBRATED WITH STAMPS

The Royal Academy of Engineering's Taylor Centre features on one of the Isle of Man stamps that celebrate Dr John C Taylor's achievements

Two Fellows of the Royal Academy of Engineering have been recognised on recent issues of postage stamps: Dr John C Taylor OBE FREng FRS features on a set of six Isle of Man stamps, and Carlos Ghosn KBE FREng has been honoured on a Lebanese postage stamp.

Dr Taylor, an Isle of Man resident, has over 400 patents and invented the temperature- and current-sensitive safety controls that are used in small electric motors for appliances. He developed the controls that turn kettles off once they have boiled, as well as the cordless kettle.

The set of stamps focuses on Dr Taylor's inventions and personal achievements. One stamp commemorates the bimetal kettle switch, which is used over a billion times a day worldwide. The Otter G switch, a small temperature-sensitive control that Dr Taylor invented in the 1960s, features on another stamp. A third stamp highlights Dr Taylor's commitment to inspiring the next generation of engineers, and includes an image of the Academy's Taylor Centre, the home of the Enterprise Hub that opened in early 2017. A generous donation from Dr Taylor helped to make the Taylor Centre possible.

Ghosn, chairman and CEO of the Renault-Nissan Alliance, is the first businessman to feature on a Lebanese stamp. He was chosen by the national post office of Lebanon, which has a tradition of creating stamps that celebrate the successes of the country's citizens. Previous collections have featured political icons and women pioneers.

3D SCANS IDENTIFY OLDEST MARINE NAVIGATION ARTEFACT

State-of-the-art scanning technology has revealed the details of the oldest-known marine navigation tool, which was discovered in a shipwreck off the coast of Oman.

Professor Mark Williams, from the Warwick Manufacturing Group at the University of Warwick, used 3D scanning technology to discover markings on the astrolabe, a tool used by mariners to measure the altitude of the sun during voyages to determine their location.

The astrolabe is believed to date from between 1495 and 1500. The ship that it was part of, the *Esmerelda*, sunk during a storm in 1503. When it was recovered in 2014, the team who discovered the artefact, led by David Mearns from Blue Water Recovery, thought it was an astrolabe but the navigational markings were not apparent. It had been under water for over 500 years so there was significant degradation to its surface caused by corrosion and wear. The scans revealed 18 very fine markings around the edge of the disc, almost invisible to the human eye, which were each separated by five degrees, confirming the recovery team's beliefs.

Professor Williams' team used a seven-axis manual measurement arm mounted with a 3D laser scanner, which can produce 80,000 measurement points per second along a laser stripe that is moved across the object's surface to characterise its geometry. This produced a high-density point cloud that was used to create a 3D model of the astrolabe accurate to within 0.05 millimetres.

The astrolabe's markings were difficult to detect after 500 years underwater (left), but the resolution of the 3D data enabled Professor Williams' team to zoom in and identify the marks

Commenting on the finding, Professor Williams said: "This technology is typically used within engineering for the measurement of components and quality assurance. The portability, high accuracy and non-invasive nature of this technology makes it ideal for the characterisation of rare artefacts."

Both Professor Williams and David Mearns appeared at an *Ingenia* Live! event in September 2017, where they spoke about the technology and how it had helped to identify the astrolabe as well as some of the other 3,000 artefacts discovered in and around the shipwreck.

Words: Gemma Hummerston, Portia Sale, Tereza Pultarova

ENGINEERING INNOVATIONS AT THE DESIGN MUSEUM

The Sewco wheelchair is just one innovation on display at the Beazley Designs of the Year Exhibition. The wheelchair's set of retractable tracks allow users to travel up and down steps without assistance

The Design Museum has launched its latest Beazley Designs of the Year exhibition. Now in its 10th year, the exhibition brings together 60 global projects that have made an outstanding contribution to design in six categories: architecture, digital, fashion, graphics, product and transport.

Across the categories, the designs include: a wheelchair that has a set of retractable rubber tracks, an earpiece that translates languages, and a text messaging service and online tool that provides updates and useful information to refugees.

The transport category features: Olli, the world's first 3D-printed self-driving bus, which can carry up to 12 passengers, and can work either independently or as part of network of smart vehicles; the Autonomous Rail Rapid Transit system, a self-driving electric vehicle that is guided by a double-dashed line painted on the street rather than tracks; and SeaBubbles, a water taxi created by two aeronautical engineers that has zero noise, no CO_2 emissions, and a self-charging dock that returns energy to the grid.

The winners of each category and an overall winner will be decided by a jury of industry experts in January 2018. The exhibition runs in London until 28 January 2018. Further information can be found at **designmuseum.org**

ROBOT-OPERATED FARM PRODUCES FIRST HARVEST

In early September, the world's first farm run by robots produced its first ever harvest, 4.5 tonnes of spring barley, using a fully autonomous combine harvester.

Hands Free Hectare is a site run by Harper Adams University in Shropshire. Everything in the process of growing the spring barley crop, including sowing, fertilising and collecting samples, was done by autonomous vehicles.

Instead of building the machines from scratch, the engineers bought commercially available agricultural technology and paired it with available open-source software used in hobbyist drones. They then fitted the tractors and harvesters with actuators and robotic arms that would allow them to control the machines remotely. The next step was making the machines run fully autonomously without any human supervision.

The vehicles' navigation is entirely based on GPS and they drive towards pre-determined targets, where there are different actions designed to be carried out.

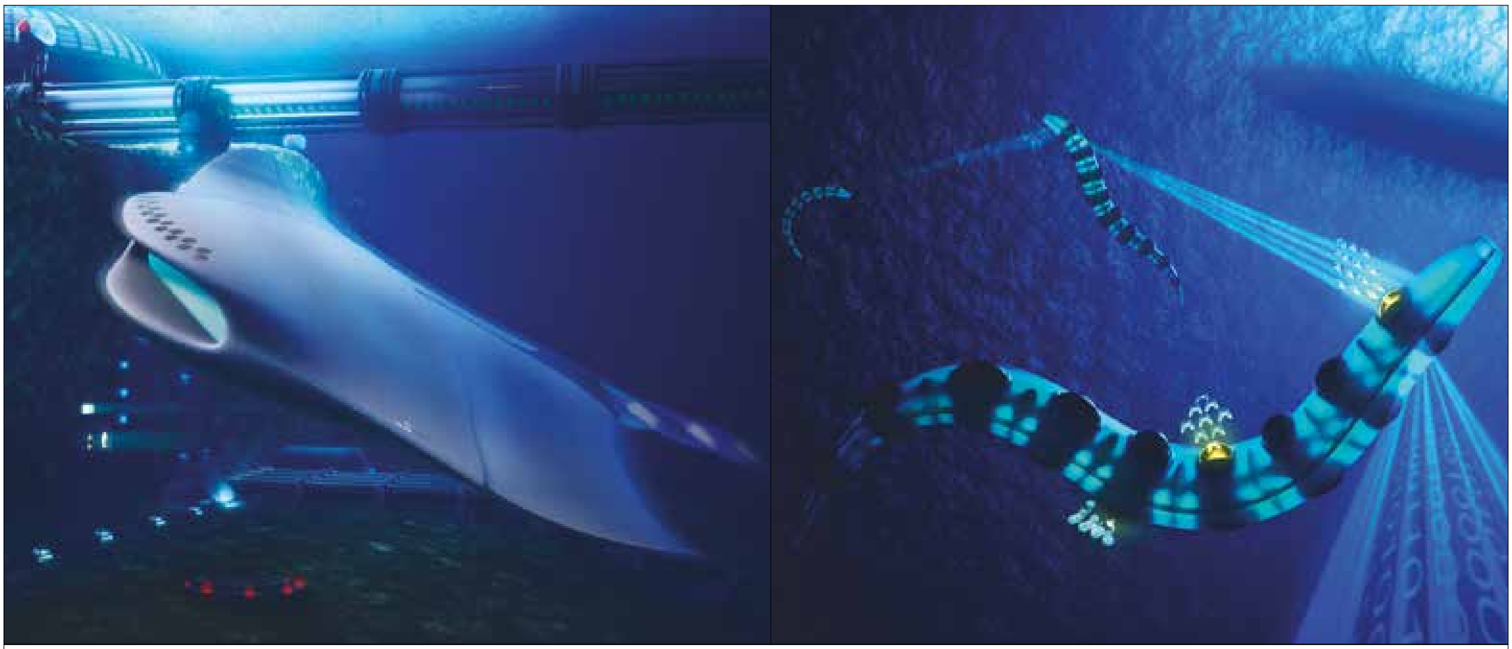
The researchers believe that robotic technology will enable future farmers to improve their yields, something that will be necessary to feed the world's growing population. Herbicides and fertilisers could be distributed more accurately and only where they are needed. Moreover, the lighter machines would not damage the soil as much as large heavy machinery does.

Hand Free Hectare's spring barley crop is harvested by an autonomous combine harvester

"At the moment, the machines used in agriculture are large, they operate and cover large areas of ground quickly but with it comes inaccuracy," explained Martin Abell, who works for precision agriculture firm Precision Decisions, which has been collaborating with the university on the project. "Small machines working with smaller working widths would provide a means to bring the resolution down. Instead of a 30-metre sprayer, you would have a six-metre sprayer and that is just the beginning of making things smaller."

The Harper Adams team plans to use the robotically harvested spring barley to make a limited edition of 'hands free' beer that would be distributed to the project's partners as a thank-you.

YOUNG ENGINEERS DESIGN FUTURISTIC SUBMARINES



A digitally created image of what the proposed submarine would look like (left). The manta ray-shaped vessel would act as a mothership and deploy smaller underwater vehicles, such as the unmanned eel-shaped concepts (right)

The Royal Navy has unveiled several futuristic submarine concepts as part of its Nautilus 100 project, which aims to mark the 100th anniversary of the launch of the USS Nautilus, the world's first nuclear-powered submarine.

The Nautilus 100 project began in June 2017, organised by the Royal Navy in association with UKNEST (UK Naval Engineering, Science and Technology Forum). Rear Admiral Tim Hodgson, the Ministry of Defence's Director of Submarine Capability, challenged a group of UKNEST apprentices and graduates to imagine what the underwater battle space and Royal Naval submarine fleet might look like in 100 years, considering the new technologies that would be available to inspire the next generation of scientists and engineers.

The group of apprentices and graduates used this as a challenge for their futuristic submarine idea, creating a 'mothership' concept that encompassed complex systems, which could apply rapidly developing technology to make future submarines easier to construct, more effective and cheaper to run. This included a crewed mothership shaped like a manta ray that could change its form using smart materials. The group planned for the vessel to have a 3D-printed hull created from light but strong acrylic materials, and that it would have two propulsion systems: one for silent and efficient cruising for thousands of miles at up to 30 knots, which would be powered by hybrid algae-electric propulsion; the other for short bursts of high speed, powered by a Casimir force battery that uses zero-point energy to produce enormous power. The submarine would be cloaked in a pocket of air to reduce drag and enable it to travel at speeds of up to 150 knots. This air pocket would be formed by bubbles created by bow-mounted laser emitters boiling the water in front of the submarine.

The young engineers also designed smaller, autonomous vehicles that could be deployed from the manta ray submarine. This included eel-shaped underwater vehicles that could travel hundreds of kilometres using a sine wave propulsion motion. These would also be able to eject sensor pods equipped with 3D-printed micro drones that communicate with each other to provide detailed information on targets. Traditional torpedo and missile systems were imagined to be replaced by flying fish swarm drones that would be powered by microturbines in the air, with intake and exhaust vents that would open and then close as the drones reentered the water, where they would be powered by plasma batteries.

It is hoped that these concepts will inspire technology development projects and that some of the ideas will eventually be used in real-life applications.

Commander Peter Pipkin, the Royal Navy's Fleet Robotics Officer, said: "Today's Royal Navy is one of the most technologically advanced forces in the world, and that's because we have always sought to think differently and come up with ideas that challenge traditional approaches. If only 10% of these ideas become reality, it will put us at the cutting edge of future warfare and defence operations."

HOW I GOT HERE

Q&A

ANNA PLOSZAJSKI
MATERIALS ENGINEER

Anna Ploszajski is a materials engineer and science communicator who wants to bring materials engineering to the wider public. She is currently completing an engineering doctorate in hydrogen storage materials at UCL.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

Growing up, my career aspirations varied wildly, from architect to classical trumpet player. I was an all-rounder academically, but I chose to study maths, further maths, physics and music at A level, aiming to study physics at university – nobody told me about engineering. When I applied to the University of Oxford, its materials department was low on applicants, so they invited me to interview for both subjects. To cut a long story short, on Christmas Eve I received a letter offering me a place to study materials science at Oxford. Rapid Googling ensued, but I accepted the place, and this happy accident saw me spend four years studying the best subject in the world. For me, it was the perfect blend of hard science and practical engineering applications. I became obsessed, but was sure to maintain a healthy balance of staying out too late and playing my trumpet in every musical group I could find.

HOW DID YOU GET TO WHERE YOU ARE NOW?

I spent my fourth year at Oxford researching hydrogen storage composites with a local spin-out company, Cella Energy. I loved flexing my new materials muscles in such a fast-paced environment and my voice was really valued; in fact, my work was central to the patent that the company is now based on. I was certain that I wanted to be an industrial researcher, but I needed a doctorate. Cella Energy sponsored me through an engineering doctorate (EngD) at UCL, which is an alternative to a traditional PhD that involves PhD-style research while working directly with a company. I also took a course in public engagement run by Steve Cross, then head of public engagement at UCL, and was somehow convinced to participate in Bright Club, a stand-up comedy night from academics and researchers. It wasn't a complete disaster so I did it again and again. For the last year, I've been a member of Steve Cross's Talent Factory, a group of up-and-coming science communicators, which has helped this side of my career to really take off. I now split my time between finishing my EngD and working as a freelance writer, communicator, trainer and stand-up comedian focusing on materials engineering.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

Being awarded an RAEng Engineers Trust Young Engineer of the Year Award was a really nice recognition of my contribution to engineering so far. Balancing doctorate work by day and stand-up comedy by night has been taxing, and it wouldn't have been possible without the support of the Talent Factory and a very understanding supervisor. It was a real privilege to be recognised next to four other astoundingly impressive early-

Anna performs stand-up comedy about engineering © Steve Cross

career engineers and I hope it will open the door to me being involved in other Royal Academy of Engineering activities.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

I imagine that being a materials engineer is similar to being a talented photographer, in that you find beauty in the everyday environment. For example, I love it when a component of my bike fractures and I can work out why, and people probably think I'm bonkers when I pick up random objects to find out what they are made from. My friends have recently developed a habit of pointing at stuff (clouds, beer, cats, and so on) and asking 'is this a material?'. I pretend to be annoyed but I secretly think it's a brilliant game because it makes you think about the stuff that's around us. You have to zoom in and ask: what are these atoms up to that make this thing so heavy, so fluffy, so tasty? That's materials engineering.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

I'm training to swim the English Channel in July, so a typical weekday will start with an hour in my local lido. For the last few months, this has been followed by a good few hours working on my thesis. My latest experiment was really cool: 4D X-ray computed tomography on my hydrogen storage materials. In other words, I was watching the gas coming out of the materials in 3D, as a function of time. The analysis of the results has been quite involved but it's been fascinating work. The freelance work is hugely varied, and that's what I love most about it. Specific work booked in during the day might be delivering communications workshops to engineers or compèring a science-themed event for school-aged children. Other freelance work includes writing funding applications, preparing new comedy material, experimenting with new demos, writing for magazines, books and newspapers, producing my podcast or pitching for new work. In the evenings, I'll typically be found performing stand-up comedy a couple of times a week, or at rehearsals with my bands or orchestra.

CAN YOU TELL ME ABOUT YOUR WORK PROMOTING ENGINEERING?

Engineering in this country is suffering because of the poor public understanding of what engineers do and who they are. This is deeply engrained in our culture, and engineering needs a dramatic rebrand if we are to plug the widening skills gap. This is my mission, and I do this through as varied media as possible; there's the stand-up comedy that has taught me about the importance of understanding and reading your audience, as well as general performance elements, such as body language and rhythm. I love writing because it gives me the time to be more creative with language than the live performances; I particularly enjoyed contributing a chapter about smart materials to Jim Al-Khalili's book about the future called *What's Next?* I produce my own podcast about materials called *'rial talk*. In each episode, I interview someone about a material that means something to them: a potter about clay, a vintage jewellery enthusiast about Bakelite, a dentist about mercury. The aim is to demonstrate that all these people are materials experts, and that engineering is everywhere.

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

Get making! At its core, engineering is about creating things to make the world better, whether that's software, skyscrapers or new materials. Whatever interests you – music, gaming, eating cake – you can engineer it. There really is no substitute for getting your hands dirty and you don't need much to get started. Drive your parents mad by taking stuff apart, they'll forgive you later when you can fix their iPad for them.

WHAT'S NEXT FOR YOU?

Immediately after I submit my thesis, I plan to take the freelance engagement work full time for a few months. I've got some exciting large-scale projects planned and I'm interested to see how far I can go with them. I want to develop hour-long shows to take to schools and science festivals, as well as the Edinburgh Fringe Festival, and I've got the seeds of a book idea up my sleeve too. I am swimming the English Channel next July, which will require a bulky training regime, so freelancing will give me the flexibility I need for the best chance of landing in France. However, ultimately there's nothing like being on the frontline of research, so I plan to find a postdoctoral position within the next year, with a slight change of focus to smart materials engineering and 4D printing.

QUICK-FIRE FACTS

Age: **26**

Qualifications: **MEng, MRes, EngD (nearly!)**

Biggest inspiration: **Mary Jackson, former mathematician and aerospace engineer at NASA**

Most-used technology: **my laptop**

Three words that describe you: **aquatic trumpeting engineer**

OPINION

HOW ENGINEERING CAN TAKE ITS PLACE IN THE SPOTLIGHT

Engineering is at the core of modern society, underpinning every sector and contributing at least £280 billion to the UK economy. More young people from a diverse range of backgrounds are needed in the profession to ensure that the UK maintains its place as a global leader in innovation. John Hayes CBE MP, Minister of State for the Department of Transport, outlines how the government-led Year of Engineering in 2018 aims to raise awareness of the excitement and variety that engineering offers.


The Rt Hon John Hayes CBE MP

The American president Herbert Hoover, who began his career as a mining engineer, once travelled to Oxford to debate whether the city's university should include engineering in its teaching. He argued that our country lagged far behind his own in the standing that we afforded engineering, and that "not until Oxford and Cambridge recognised engineering as a profession equal to others would engineering secure its due quota of the best brains".

Recounting the experience later, he wrote that: "Soon after the Oxford discussions, I returned to America. At my ship's table sat an English lady of great cultivation, who contributed much to the evanescent conversation… We were coming up New York Harbour at the final farewell when she turned to me and said: 'I hope you will forgive my dreadful curiosity, but I should like awfully to know – what is your profession?'

"I replied that I was an engineer. She emitted an involuntary exclamation, and 'Why, I thought you were a gentleman!'."

Hoover did not let this experience dampen his enthusiasm for promoting education in engineering. As he put it: "engineering training deals with the exact sciences. That sort of exactness makes for truth and conscience. It might be good for the world if more men had that sort of mental start in life."

I agree, adding only that it would be better still for the world if more women and young people from black, Asian and minority ethnic (BAME) backgrounds received training in engineering.

In fact, Hoover's vision is mirrored in the core vision of our landmark campaign to make 2018 the Year of Engineering. The government is joining forces with hundreds of organisations to boost the standing of engineering as a profession and increase the numbers of women and BAME people choosing engineering as a career.

It makes sense to choose 2018 as our Year of Engineering. In transport alone – my field of responsibility – 2018 is the year

2018 heralds a new era of engineering of all kinds. We are anticipating – and already witnessing – breakthroughs in medical, space, automotive, food, agricultural and other fields of engineering, many of them fuelled by the rise of big data, machine learning and artificial intelligence

that Crossrail, Europe's largest engineering project, opens to passengers; it's the year that we complete Thameslink; and the year that construction begins in earnest on HS2 (High Speed Two), which, in inheriting Crossrail's mantle as Europe's biggest project, will do for the country what Crossrail is doing for London.

These are just a sample of the government's colossal infrastructure investment programme, bigger than any in living memory. However, it is not just the scale of what we are seeking to achieve now; 2018 heralds a new era of engineering of all kinds. We are anticipating – and already witnessing – breakthroughs in medical, space, automotive, food, agricultural and other fields of engineering, many of them fuelled by the rise of big data, machine learning and artificial intelligence. The engineer of 2018 and beyond will be as likely to wield a virtual reality headset as a spanner.

So, one might say that there has rarely been a better time to be an engineer in Britain. Yet paradoxically, we also face a serious shortage of people entering and remaining in the profession. The engineering profession has said that it needs 265,000 skilled entrants a year, every year, until 2024, simply to keep up with demand, because so far nothing like that number of people are entering the industry. Half of engineering companies say that the shortage is having a significant effect on productivity and growth.

That is bad news for engineering and bad news for Britain, and it will make achieving our infrastructure ambitions much more challenging. Yet for some, it is a particular loss. There are those in our society who would thrive as engineers, but for a variety of reasons fail to break into the profession. Such lost numbers means that only one in eight engineers is female – one of the worst ratios in Europe – and only one in 20 is non-white.

The Year of Engineering is our chance to turn this around, to get many more young people from all sorts of backgrounds inspired by what they could achieve. We want recruits of all ages to join the industry, but we know that students encounter the biggest barriers to entry while they are still young. Before they even start secondary school, many girls start to describe engineering as a job for boys. Shortly after, they are expected to make subject choices that will define their careers, often inadvertently barring themselves from pursuing an engineering apprenticeship or university course.

Next year, as pupils in schools and colleges up and down the country choose their future careers, I want engineers and engineering firms to speak up, loud and clear, that engineering is for everyone. I want companies to open their doors for student visits and work experience. I want engineers to speak at school assemblies and careers fairs. I want young people and their families to take a closer look at engineering, and to discover that the profession is about imagination, creativity and opportunity. A hundred years or more since his visit to Oxford, I want us to say afresh with Hoover that: "It is a great profession. There is the fascination of watching a figment of the imagination emerge through the aid of science to a plan on paper. Then it moves to realisation in stone or metal or energy. Then it brings jobs and homes. Then it elevates the standards of living and adds to the comforts of life. That is the engineer's high privilege."

Over 300 organisations have already pledged their support, and in January we will be launching the campaign with a week of events in schools, museums and communities across the country. A year of engineering open-door days, exhibitions, school visits and a great deal else will follow. There is much to be done, and by our enterprise and endeavour much we can do, and so make the Year of Engineering memorable not just for 12 months but for the future it shapes, crafted by a new generation of engineers.

BIOGRAPHY

The Rt Hon John Hayes CBE MP was reappointed as Minister of State at the Department for Transport following the general election of 8 June 2017, a position he has held since 15 July 2016. The position includes responsibility for transport skills, and he is the lead minister for the Year of Engineering. He has been Conservative MP for South Holland and The Deepings since 1997.

The Year of Engineering launches in January 2018. To find out more, visit **www.dft.gov.uk/year-of-engineering-2018** or follow **@YoEgovuk** on Twitter.

The Bloodhound Supersonic Car reached speeds of 320 kph during testing at Cornwall Airport Newquay in October 2017. The tests have set in motion the process for the car's land speed world record attempt in South Africa in 2018 © Stefan Marjoram

READY TO BREAK RECORDS

In October 2017, almost a decade of engineering development finally came to fruition when the Bloodhound Supersonic Car embarked upon its first tests at Newquay Airport. Technology journalist Richard Gray spoke to Mark Chapman, Bloodhound's Engineering Director, about the challenges that were overcome in the car's creation and how it will attempt to break the world land speed record in South Africa in 2018.

With an ear-splitting roar, the car's wheels begin to turn, slowly at first, but within seconds all that is visible of the £30 million vehicle is the flame spitting from its exhaust in the distance.

The test run is over almost too quickly, but this was the fastest and furthest the Bloodhound Supersonic Car (SSC) has travelled so far. It marks a small but significant step towards the goal of turning it into the fastest vehicle to ever drive on land.

The British team behind the car is attempting to break a land speed record that has stood for more than 20 years. That record was set when Royal Air Force (RAF) pilot Andy Green hurtled across Black Rock Desert in Nevada, USA, at 1,227 kilometres per hour (kph) in 1997. On that occasion, he was sat behind the wheel of another British-built, jet-powered car called Thrust SSC, and he will now try to break his own record in Bloodhound.

Designed and built by a dedicated team of engineers, the pencil-shaped car is intended to do something that only military jets and Concorde have done before: travel at more than 1,600 kph.

In a series of brief trips down the 2.7 kilometres of the runway at Aerohub, Cornwall Airport Newquay, in October 2017, the car was driven up to 305 kph. Then on 26 October, in front of thousands of members of the public, Bloodhound was taken above 320 kph for the first time, marking a major milestone on the journey towards breaking the record.

POWERED BY JET ENGINE

For those involved who have spent up to 10 years working on the project, hearing the engine's reheat (afterburner) kick in for the first time was a visceral moment. The tests have provided some important answers that were needed before Bloodhound can be sent to South Africa for its first world record attempt in 2018.

Chief among these is the low speed capability of the jet engine intake mounted above the cockpit. Bloodhound is like a jet fighter with no wings, getting around half of its thrust from a Eurofighter Typhoon's EJ200 jet engine.

On the Typhoon, this military turbofan engine is designed to work best at speeds of over 1,300 kph when air is rushing through it. At full power, it would be able to suck all the air out of an average house in around three seconds. However, at lower speeds, the jet engine intake may not get enough air into the engine to combust all the fuel at full throttle. Therefore, the team needed to test how it would perform at very low speeds to know when full power could be applied.

The Bloodhound was fitted with a jet engine designed for use in military fighter aircraft. This proved to be something of a challenge and resulted in changes to the shape of the car © Stefan Marjoram

Before the test runs in Newquay, the engine was not expected to be able to cope with full power until the car reached around 130 kph. This was what the team had learned from the two Rolls-Royce Spey turbofans that had been used on the Thrust SSC. However, Green found that he could apply full power to the Bloodhound while stationary, which allowed the car to accelerate even faster than expected.

Fitting a jet engine, designed for a military fighter capable of flying at 1,550 kph, onto a car was no easy task. The EJ200 engine, which was provided by the Ministry of Defence, weighs nearly 1,000 kilograms and produces 90 kilonewtons (kN) of thrust. On an aircraft, the engine is set so that if it loses its connection with its control unit, it will continue operating so that the plane can stay in the air. In Bloodhound, this function needed to be circumvented to avoid the car from careering off into the desert. The team added a manually operated valve – operated by the sort of accelerator pedal you might find in a normal car – so that Green

The rear end of the Bloodhound, including the suspension, had to be redesigned to cope with the extra weight from the cluster of three rockets that was added during development © Stefan Marjoram

can manually shut off the jet engine's fuel supply.

Jet engines are designed to work best at altitude. At ground level, Bloodhound will be travelling far faster than a Typhoon would on the ground, so it will push the engine to its limits. With this in mind, the air intake duct for the engine had to be specially designed to ensure a smooth stable flow. The original Bloodhound designs gave the car twin intake ducts, but airflow modelling revealed that this would create high levels of turbulence where the two ducts joined. Instead, the team changed the design so that a single, massive intake duct was positioned over the cockpit canopy.

This also led to changes to the overall shape of the car to ensure that the flow of air into the jet engine could be maintained. The engine itself cannot operate properly with air travelling into it above the speed of sound as this can cause shockwaves on its fan blades and cause it to choke. To overcome this, the shape of the cockpit canopy and the intake duct itself have been designed to slow down air to below supersonic speeds. A series of tiny shockwaves will be created as air passes over them, slowing the air from 1,600 kph to around 965 kph in under a metre.

However, the jet engine will only get the car up to a speed of 1,050 kph. To reach 1,600 kph, it will need some rocket power. Initially, Bloodhound was due to be powered by a single Falcon hybrid rocket, but in 2013 this was changed in favour of a cluster of three smaller rockets built by Norwegian company Nammo. These rockets will be added to the back of the vehicle for the record attempts.

Unfortunately, to accommodate this cluster of rockets, the rear end of the car, including the suspension, had to be redeveloped to cope with the extra weight. It was just one of the many challenges that the project has successfully tackled.

STREAMLINING THE DESIGN

The project was first announced in 2008, and has undergone much development. The goal was to have the Bloodhound running by 2012, but because it was such a major aerodynamic and engineering challenge, it took nearly three years to find the aerodynamic shape needed to keep the car safely on the ground at such high speeds.

Without access to expensive wind tunnels, the team was reliant upon sophisticated computer modelling to assess whether designs might work. One early tweak at the end of 2009 changed the configuration of the car so that the jet engine sat on top and the rocket underneath in an effort to reduce unwanted lift at the rear of the vehicle, and to simplify the design. However, aerodynamic tests suggested that this configuration could still lead to more than 100 kN of lift, which would be catastrophic for the car as it raced across the desert.

The team went back to the drawing board, but it was taking around 8 to 12 weeks to analyse each design model for its aerodynamic flow. With the help of some experts at analysis software producers MathWorks, the team introduced a new systematic way of assessing the data that allowed them to begin analysing designs in around 30 minutes. Within three months, it could produce what would remain broadly the final shape of the car. The key was minimising the rear wheel track width and the precise shape of the rear body of the car to ensure it would remain stable at high speeds.

The wheels have posed a particular problem for the Bloodhound team. During the test in Newquay, the vehicle was mounted on a set of four rubber tyres that were originally manufactured for the English Electric Lightning jet fighter; however, the car will need

The Boodhound's steering suspension joint is split and truncated, and the two parts move indepently of each other. This gives the best suspension stiffness and prevents the wheel from flexing off line, which can cause instability © Stefan Marjoram

something far stronger when it is time for the record attempt. The difficulty lies in finding a material that is capable of withstanding more than 10,000 revolutions per minute and loads of 50,000 G at the wheel rim.

A traditional wheel on a road car has a distinctive C-shape with the hub in the middle if you were to cut through it. This design helps to give cars responsive and predictable steering as the pivot point can be located inside the wheel hub at its centre. Unfortunately, at 1,600 kph, that C-shape cross-section begins to distort and break apart.

Instead, the Bloodhound team changed how the car was steered so that they could use a far simpler symmetric wheel, forged from solid disks of an aluminium-zinc alloy. These symmetric wheels rotate more like the fan from a gas turbine and spin tests at the Rolls-Royce facility in Derby demonstrated that they can easily cope with the loads they will face.

However, ensuring that these symmetric wheels still turn around their centre point meant using a different approach to steering. Road cars tend to use a traditional wishbone shape for the swivel joint that connects the wheel to the car. Bloodhound uses a suspension joint where the wishbone is split and truncated; these parts move independently to create what is known as a virtual steering axis. This allows the wheels to rotate about their centres as if the pivot point was located inside the wheel hub.

In a standard car, where a driver might want to turn the wheels up to 20 degrees while motoring along, a virtual steering assembly like this one would feel weird and not respond in ways that the driver might expect. However, at high speeds, Bloodhound will only need tiny adjustments to stay on course, so a whole rotation of the steering wheel from lock to lock will only turn the wheels about five degrees. It means that the car has an appalling turning circle of about 240 metres – Bloodhound is not the car to practise three-point turns in. Exactly how the steering performed in the real world only became clear during the tests in Newquay.

Green's initial feedback was surprising: the car handled like it was driving along rails. Analysis of some of the data gathered during the test should reveal more about how the steering will perform at higher speeds.

CREATIVE THINKING

The technical challenges faced when building a supersonic car able to break through the 1,600 kph barrier have brought unexpected hurdles, and issues with funding also led to some delays – as with many world record attempts across the globe. The team had hoped to travel to South Africa to attempt the world record in 2017, but a development hiatus last year to raise more funding saw the record attempt rescheduled until 2018.

So far, the development of Bloodhound has cost £30 million, and it is expected to cost a further £30 million to complete and run the vehicle for its record attempts. However, this £60 million price tag is a fraction of the cost of running a Formula One car for just one year – something that can cost the top teams up to £250 million annually.

These budget constraints have forced the Bloodhound team to think creatively about some of the solutions needed to build the car. A good example of this can be found with the car's steering wheel, which has been 3D printed from titanium using moulds of Green's grip as the basis. During the record attempts, the acceleration forces passing through Green's arms to the wheel will reach up to 300 kilograms, which is why it needed to be made from metal.

Prototypes of the Bloodhound's steering wheel were 3D printed using moulds of driver Andy Green's grip. The final design (bottom) was 3D printed in titanium by Renishaw © Stefan Marjoram

To make controlling the vehicle's systems easier when facing such high acceleration forces, the steering wheel also has three switches mounted on each side to fire the brake chutes, air brakes, radio and abort mission sequence. Two triggers on the back of the wheel control the firing of the rockets.

Rather than design its own triggers, or buy some from the space industry where they could cost thousands of pounds, the Bloodhound team looked at the electric power tools they were using. These devices are used every weekend by DIY enthusiasts in homes around the world, where they are exposed to damp, dust and vibrations, yet keep working. Costing just £8.99 each, installing a pair of triggers that are already used in power tools seemed like a neat solution to something that could have eaten up valuable time and money.

Similarly, the valving system on the rocket engines borrowed technology from the oil and gas industry rather than using expensive space industry components. The team modified high-pressure seals that are used on the shafts of high-speed machinery such as drills and found that they worked just as well in tests.

SET FOR SOUTH AFRICA

While the rockets themselves were not fitted to the car for Newquay, the two test runs have helped to reveal more information about how Bloodhound will perform that could not be obtained from computer models.

The car's braking performance, for example, is a key deciding factor in how fast it will be able to go when it is taken out to the desert in South Africa for the record attempts. The car will hurtle across a huge dried-up lakebed called Hakskeenpan, in the arid north-west corner of the country.

An 18-kilometre-long track has been painstakingly cleared across the mud and salt flat, with more than 16,000 tonnes of stone removed by hand; but slowing the car down from around 1,600 kph could take between six and eight kilometres. Understanding how the air brakes and wheel brakes perform in the real world should help give a clearer idea of how much stopping distance the car will need, and how much space it will have to accelerate.

The tests in Newquay have also allowed the Bloodhound team to get first-hand experience with the car, allowing the support crew to put the procedures they have been trained on into practice.

They have allowed Green to experience what the car will be like to drive: how the throttle and brake actions work, and how the steering responds. It has also given him an idea of the vibration and noise he might have to endure.

The sound levels produced by the jet engine, the cluster of rockets and the V8 engine that is being used to pump the rocket's oxidiser fuel, are expected to generate more than 140 decibels. The car will begin to outrun its own soundwaves when it gets above 1,200 kph, but the shockwaves produced by the canopy and the jet intake are still expected to lead to noise levels of more than 120 decibels inside the cockpit.

The cockpit itself has been designed to protect Green not just from the noise, but also the risk of material being thrown up from the desert floor or off the wheels. It is surrounded by ballistic plates that have been tested by firing metal projectiles at them.

Although the front of Bloodhound is made from carbon fibre, it has been reinforced with an aluminium honeycomb so that it can withstand peak aerodynamic loads of up to 3,000 kilograms per square metre. The front is also protected by a 3D-printed titanium shield to help stop the dust thrown up by the car from eroding through the bottom.

Simply seeing a vehicle that is part high-performance race car, part jet fighter and part space rocket trundle out of its hangar at Newquay was a thrill for all those involved. Watching it race down the runway brought the record a step closer.

Over the next year, the engineering team will be looking at new technologies that might improve the car even further. One of those will be to investigate using an electric motor to drive the pump that will push oxidiser into the rocket engines. Currently, the car has a Jaguar Supercharged V8 engine for the job, but an electric motor would be significantly smaller. New lightweight battery technologies or even supercapacitors could make an electric motor a real option in ways that were not practical when the system was originally designed.

Building a car that can travel faster than a bullet and is capable of crossing 4.5 football pitches laid end to end in a single second is an extreme challenge; at times, it has seemed like an almost impossible one. However, with Bloodhound now entering what feels like the final straight, it is hard not to feel just a little excited.

INSPIRING THROUGH EDUCATION

As well as breaking world records, inspiring the next generation of engineers and scientists is a major objective of the Bloodhound project. Alongside efforts to build the car, the Bloodhound team uses the details of its research, design and testing to run educational events and competitions.

In 2016 alone, more than 125,000 students in the UK participated in Bloodhound school workshops and other educational activities. This included a national rocket car championship, Race for the Line, which 4,000 schools participated in last year. Teams were challenged to build model rocket cars, which then competed at one of 120 regional race hubs. The winners then went on to race at regional and national finals over the summer.

Bloodhound also has a dedicated education team and volunteer ambassadors who visit schools to give presentations and hands-on demonstrations. At these, pupils learn about what it takes to build a 1,600 kph car and get to build their own rocket cars that they can race in the playground. Teachers can also use educational packs to help use Bloodhound to deliver parts of the STEM curriculum.

Over the next year, Bloodhound will also team up with Oracle Academy to provide two themed projects that will help students learn data analysis and Java programming skills, which will be available to classrooms and computing clubs in 120 countries around the world and will potentially inspire up to 3.5 million students.

While it is hard to measure the success of much of the educational outreach of the project, two of the universities that worked closely with Bloodhound, helping with airflow modelling, have seen the number of students applying for engineering courses rise since the project started. The University of the West of England has seen the number of engineering students at the university double since 2008, while Swansea University has seen the number of applications for aerospace engineering increase by more than two and a half times in the past five years.

(Left) Students build their own model rocket cars at Bloodhound's education centre in Bristol and (right) take part in a simulated driving experience © Stefan Marjoram

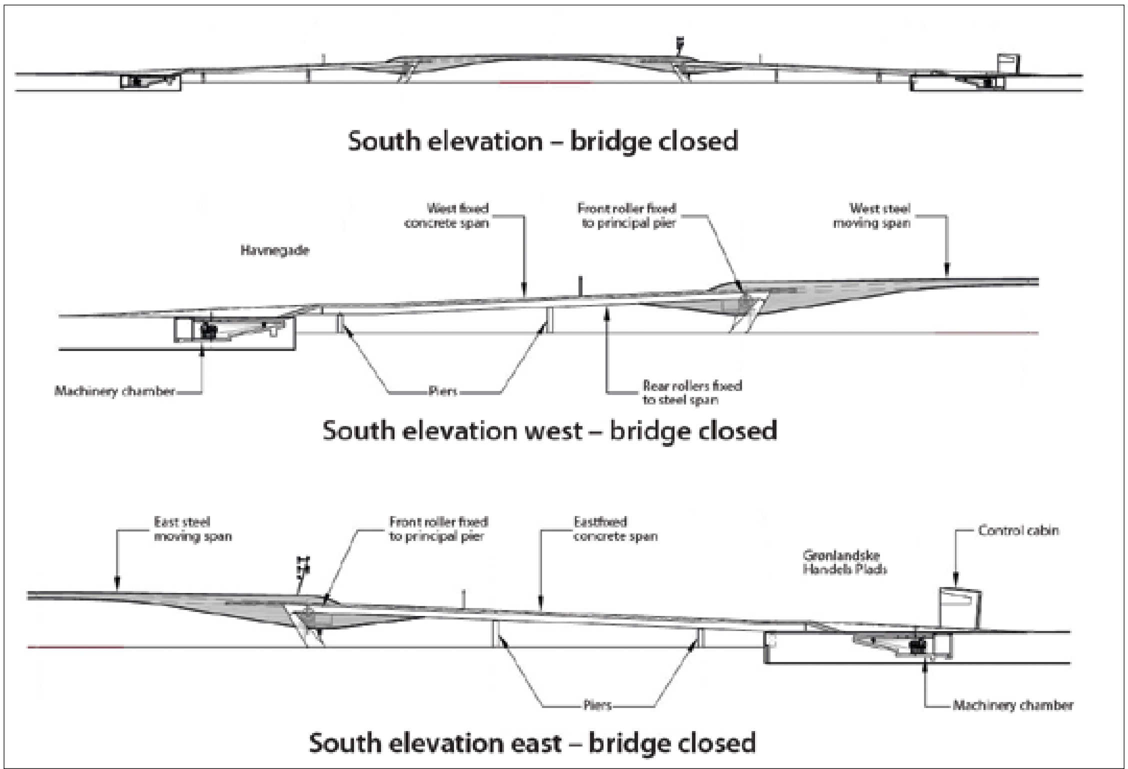
BIOGRAPHY

Mark Chapman began his career as an apprentice with British Aerospace, gaining a degree in aeronautical engineering from the University of Bath. He has worked on a huge variety of projects, from submarines and wave energy to spacecraft. In the five years before he joined the Bloodhound team, Mark was part of the team developing the F35B, the short take-off and vertical landing variant of the Joint Strike Fighter.

The middle spans on the Inner Harbour Bridge in Copenhagen slide apart to allow large boats to pass through the harbour. The spans then slide back together again and have earned the bridge the nickname *Kyssebroen* (the Kissing Bridge) © Jasper Carlberg

COPENHAGEN'S 'KISSING' BRIDGE

An innovative sliding bridge opened to the public in Copenhagen in the summer of 2016. Although the project faced various challenges and delays, the Inner Harbour Bridge *(Inderhavnsbroen)* has reduced commuting time for thousands of pedestrians and cyclists in the Danish capital each day, and has also become a popular attraction. Ian Firth FREng, Director, and Amar Bahra, Principal Engineer, both of COWI, discuss the design and the bridge's distinctive opening mechanism.



The bridge's sliding spans are cantilevering, steel box girders. Their undersides follow a smooth wave-like profile in elevation to provide the greatest structural depth at the support where the bending moment is largest. The structural depth then tapers to only 600 millimetres at the cantilever tip at midspan, where the two girders meet and interlock

Copenhagen is not a city that is short on bridges, but one was needed to link the heart of the city with Christianshavn in the east, an area that is undergoing substantial development and is home to Henning Larsen's famous new Opera House. In 2009, a design team led by engineering consultancy Flint & Neill (now COWI) won an international design competition for a new, opening pedestrian and cycle bridge over Copenhagen's Inner Harbour. Ten teams competed to design a new crossing in this historic setting and to create what would become the first bridge encountered by anyone entering Copenhagen harbour from the sea.

Aside from COWI, the team comprised architects Studio Bednarski, mechanical and electrical designers Hardesty & Hanover, and lighting designers Speirs & Major Associates. Working in a close collaborative team, the designers came up with the innovative sliding bridge idea in response to the geometry and character of the site. The idea of a bascule bridge (drawbridge) was dismissed as the designers felt that it would be an excessive visual intrusion on Copenhagen's cityscape when raised. Similarly, a swing bridge was avoided as it would have compromised free passage of vessels in adjacent canals. The required navigation channel opening was narrow compared to the overall harbour width, making it possible to withdraw the opening sections in a sliding manner and create a functional and innovative bridge.

The concept for the bridge was decided early in the process and the initial sketches reasonably reflect how the final bridge looks. Principal engineer Amar Bahra led the day-to-day design activity throughout the project. He worked regularly with Studio Bednarski to discuss the concept and develop ideas, and was in close contact with Hardesty & Hanover in New York. From the very early stages, the designers coordinated efforts to create a structure that was conceived as a closely worked combination of architecture, structure and mechanism.

There are other sliding bridges across the world that focus more on functionality than design. The team wanted to bring that sliding method of opening to an architectural pedestrian bridge that would create a surprise for onlookers who would expect the moving spans to raise or swing rather than slide. Each time it opens, two curved, steel box girders slide apart and then back again to gently meet at the centre – hence its nickname, *Kyssebroen* or the Kissing Bridge.

SLIDING MECHANISMS

The team investigated a variety of ways to drive the sliding motion of the bridge. At one point, the engineers considered a motorised front wheel that would positively engage with a track underneath the bridge in the manner of a rack and pinion to move the spans. However, a simple winch drive system was eventually chosen, which comprises a series of pulleys and steel winch ropes.

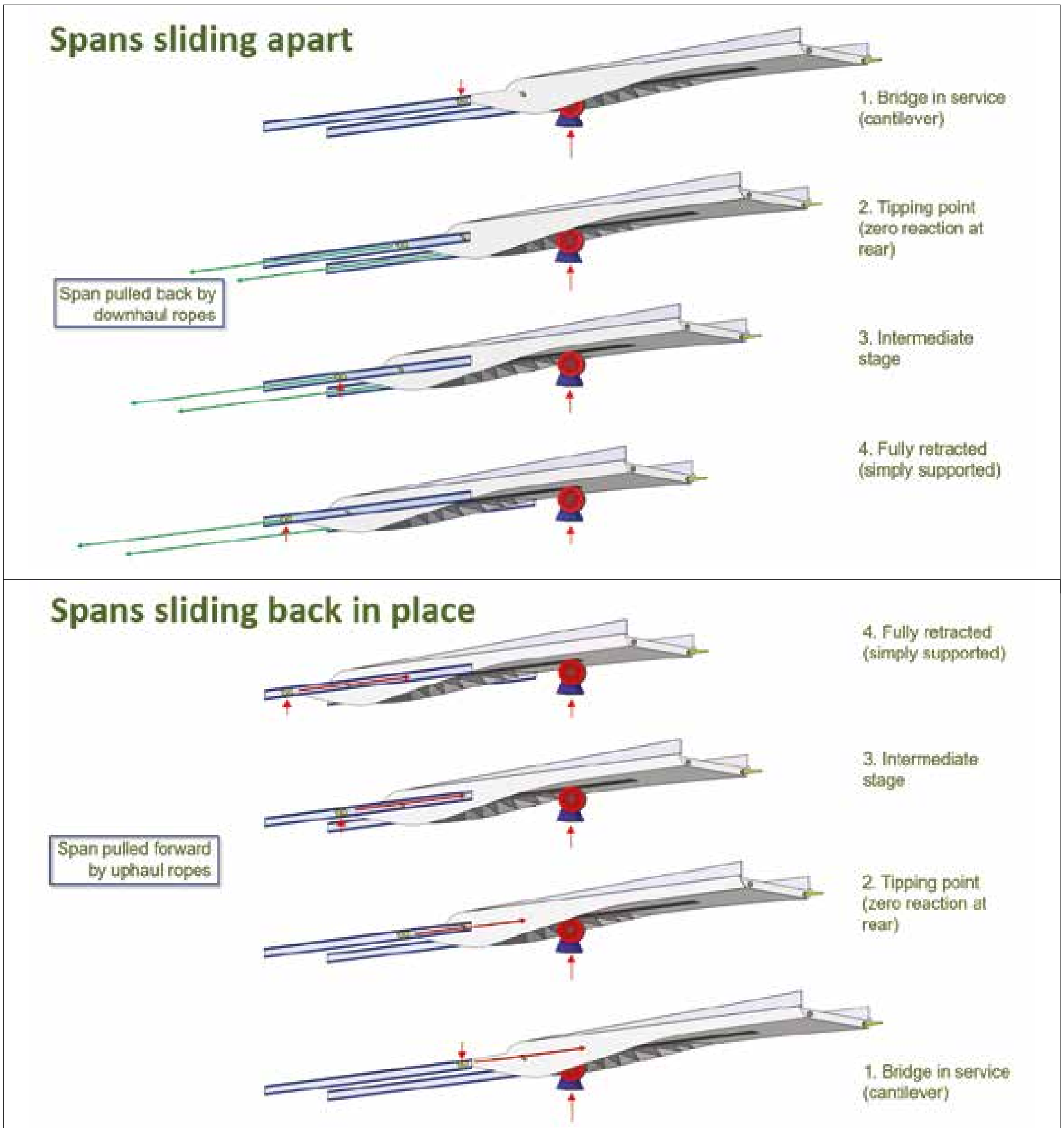
The drive mechanisms are all housed in underground chambers within the quaysides at each end of the bridge, where they can be easily accessed for operation and maintenance.

In cross section, the steel spans appear like a W shape, with the roller track in the centre of the underside and the varying depth V-shaped box cells on either side. The steel spans are supported between fixed twin concrete box girders with a wide eccentric (offset) cantilever carrying the fixed approaches (see image on page 22).

Each of the moving steel sections is about 53 metres long and weighs roughly 230 tonnes. The front support to the cantilever is provided by a pair of large 1.8 metre diameter wheels that stand on a fixed concrete pier close to the edge of the navigation channel on the bridge centreline. The rear support is provided by support wheels that roll within stainless steel tracks set in to the sides of the fixed concrete spans.

As the spans slide apart to open the bridge, the rear support points move away from the front roller support, and the moving spans change from cantilevers in their service position to simply supported girders in the fully retracted position. At each forward and rear vertical support system, there are also guide wheels that control the transverse positions of the moving spans.

A great advantage of the design is that the approaches remain open to pedestrians throughout the opening cycle. The design therefore had to consider that the opening sequence generates a complex set of possible load effects in the concrete spans owing to combinations of imposed patch loads from pedestrians together with the loads from the moving span, which change position, magnitude and direction as the spans slide.



Top: The front roller and tracks are fixed, so stay where they are while the spans are pulled back. The tipping point is when the centre of gravity of the moving span passes the front roller and the rear support reaction goes to zero and reverses. This continues until the span is fully retracted. Bottom: The winch cables repeat the operation in reverse to move the spans together again

A HIDDEN OPERATION

Concrete chambers that house the motorised winch drums are built within the east and west quaysides. There are four drums in total, one for each of the four concrete approach spans (a pair in each chamber).

Because the structural capacity and integrity of the existing historic quay walls was unknown, mini-pile foundations and ground anchors were used to support the buried concrete chambers, and on the east side, a new sheet-piled quay wall was established. The steps and ramp at each end are supported by these chambers. In fact, they are structurally separate from the approach bridge and segregated by a linear movement joint to avoid imposing significant bridge loads onto the existing quaysides.

As there is no hydraulically operated equipment in the design, the potential risk of oil spillage and consequent contamination of the harbour is avoided. The operating system is very efficient and uses very little power because of the sliding nature of the movement. This is a key aspect of the bridge's low impact, sustainable design. The mechanisms and operating systems use simple, well-proven components and arrangements, with all parts designed to permit access for inspection and maintenance.

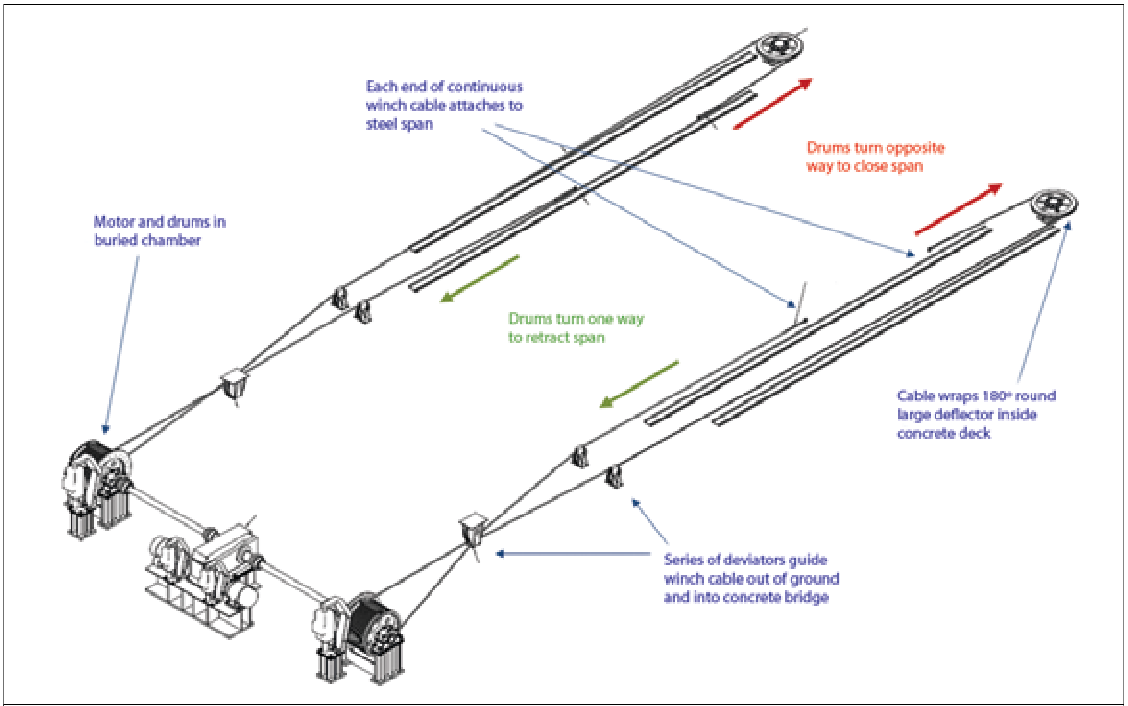
DESIGN CHALLENGES

The sinusoidal plan curvature, with east and west sides on opposite curvatures of differing magnitudes, presented certain challenges in the design and construction. Aside from driving the bridges around these curves, which required each of the four winch drums to be slightly different diameters, the curvature complicated the shape of the fixed and moving spans.

As an aside, the curved alignment led to an unfortunate rumour that there was an error in the horizontal misalignment and that this was the reason for the delayed delivery of the steel spans. Standing on one concrete span and looking straight across the water to the other concrete span, before the steel spans came to site, it did indeed appear that the spans were transversely offset. However, when the steel spans were eventually delivered (delayed because of difficulties with the steel fabricators) the curvature became obvious, and the rumoured 'misalignment' disappeared. While adding complexity, the curvature helped the engineers achieve a slightly higher navigation clearance in the middle of the bridge by providing more length.

The steel spans are highly complex in their geometry – no two cross sections are the same – and they constantly change because of the varying structural depths in elevation and the curves on plan. The moving steel girders have four inclined webs in the cross section: two inner webs and two outer webs. These are the elements that primarily resist shear and torsion (twisting) in the girder. The outer webs are formed from conical surfaces, which is easily done in steel plate, but the inner webs lie on warped surfaces that do not naturally provide good shear resistance. Therefore, the solution was to divide each inner web panel into two triangles by creasing on the diagonal and welding a tee stiffener along the inside of the crease. As these inner web elements were the closing panels of the steel box girders and internal access for welding was not possible in some places, the tee stiffeners had to stop short of the panel corners. The team had to revert to first principles and non-linear finite element modelling to prove that placing gusset plates to the ends of these stiffeners, at the relatively stiff corners of the panel, afforded them sufficient torsional restraint to ensure their stability and that of the overall web panel.

Another specific aspect that the design team had to deal with was a stringent requirement



Each drum within the buried chambers has a winch rope wrapped around it, one end of which runs along the track on the side of the concrete spans and attaches to the rear of the steel span. The other end of the rope routes through the inside of the concrete box girder, turns 180 degrees around a large deflector sheave (a pulley with a grooved wheel) and returns to attach to the steel span a few metres forward of the rear attachment point. Depending on the direction in which the drums are turned by the electric motors, the steel spans are made to either open or close
© Hardesty & Hanover

relating to pedestrian-induced vibrations. After the well-publicised problems experienced by London's Millennium Bridge in 2000, when the structure swayed from side to side as hundreds of pedestrians walked across it, the dynamic behaviour of all footbridges has been in the spotlight. COWI (while still Flint & Neill) was closely involved in the investigations and solution development for the London Millennium Bridge and is an expert in this field. For the Inner Harbour Bridge, the client wanted to allow for large synchronous crowds dancing to music in phase with the bridge motion and this resulted in the need for a series of tuned mass dampers installed within the steel spans. These control movement amplitudes by responding to, and counteracting, the bridge's motion.

The project suffered several setbacks during construction including the rejection of sub-standard fabrication and the original contractor's bankruptcy, which in turn led to considerable delays in delivery and the sourcing of a new contractor. Up until the end, concerns remained about achieving the desired quality of the finishes, and the smoothness of the geometry in the face of huge commercial and programme constraints. The designers spent a lot of time and energy trying to get the client and the new contractor to appreciate the importance of achieving the desired levels of quality.

The underside of the bridge shows where the inner webs were divided into triangles. The gives an interesting crystalline appearance when viewed from the underside as the light reflects off the water. The fixed forward rollers and the transverse guide wheel are just visible. The guide wheel runs along a slot to control the extending position of the moving spans © Cezary Bednarski

USER EXPERIENCE

Since its opening in July 2016, more than 10,000 cyclists and over 20,000 pedestrians use the bridge daily. It has dramatically reduced commuting times and improved key transit routes in the Danish capital.

The main disadvantage for bridge users on most opening bridges is the fact that they are kept well away from the action on the river, such as when a tall ship passes by. The design of the Inner Harbour Bridge provides an opportunity for the bridge user to experience the action close hand; people can stand on any one of four horizontal viewing platforms on the fixed concrete approach spans that reach towards the navigation channel, even when the bridge is operating, which enables them to be almost virtually within arm's reach of passing vessels. Many people congregate on the bridge to enjoy the views of the harbour, as well as using it as a crossing.

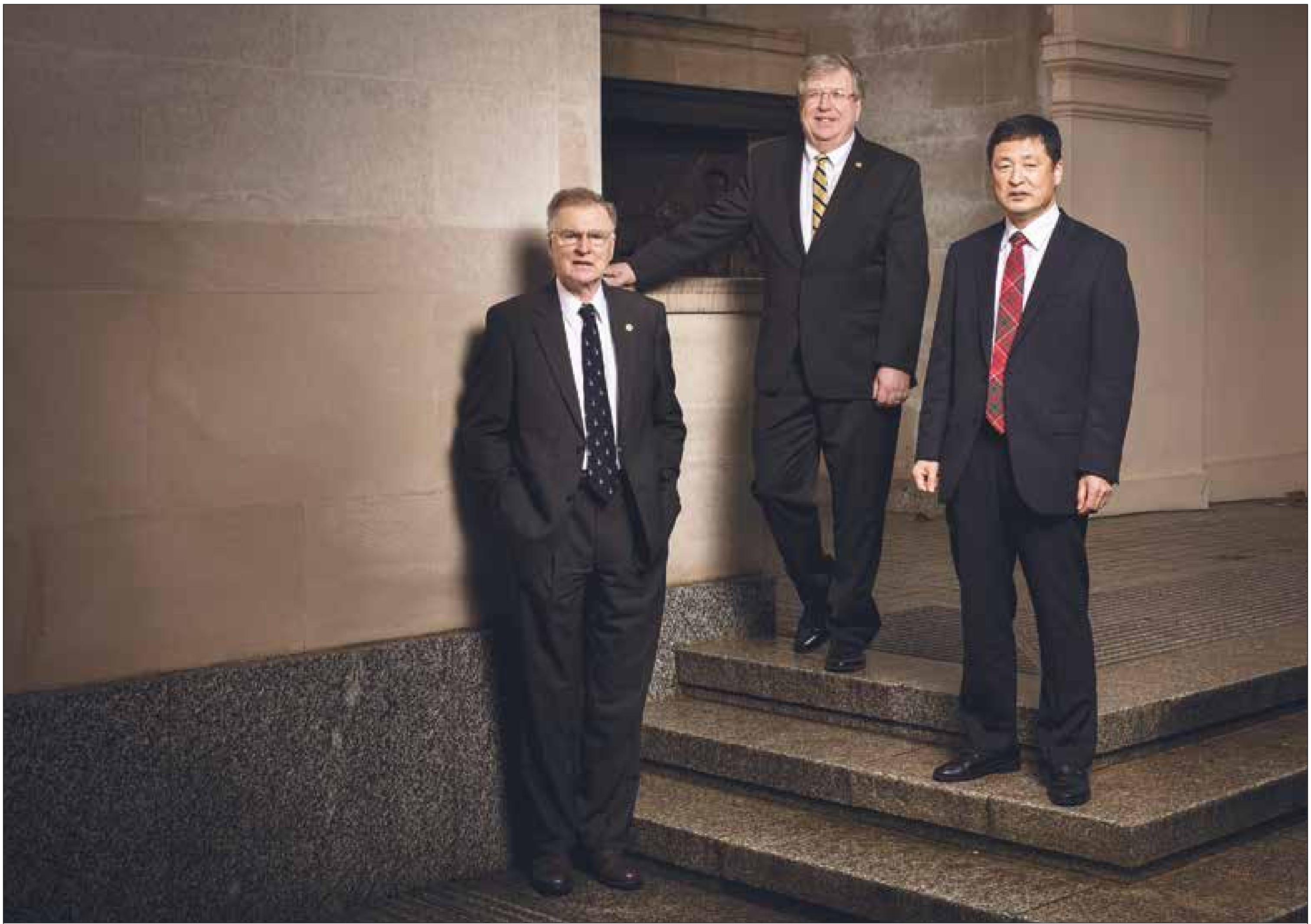
The design and apparently simple, quiet and effortless operating mechanism disguises the complexity of the structural engineering challenge of creating the bridge. The result is a bridge that is not only an important commuter route, but has also become a popular landmark in one of the most prominent parts of the city.

BIOGRAPHIES

Ian Firth FREng is Director of COWI. During his career, Ian has been involved with world-famous bridge projects including the strengthening of the Severn, Erskine and West Gate bridges, and the concept design of Stonecutters Bridge in Hong Kong. He has also been the designer of many smaller, award-winning bridges such as the Swansea Sail and Lockmeadow footbridges in the UK. Ian is an advocate of bridge-building charity, Bridges to Prosperity.

Amar Bahra is Principal Engineer at COWI, which he joined in 2008. Besides the Inner Harbour Bridge, he has worked on many high-profile projects including West Gate Bridge in Melbourne, a retractable pitch at a North London football stadium, Wimbledon No. 1 Court, Royal National Theatre, London Olympic Stadium, and Messina Bridge between Sicily and mainland Italy.

To watch the bridge in operation, please go to **www.youtube.com/watch?v=vJafdcHP73k**



(L–R) Michael Tompsett, Eric Fossum, Nobukazu Teranishi and George Smith (not pictured) received the Queen Elizabeth Prize for Engineering for three innovations that have radically changed the visual world © Jason Alden

IMAGE REVOLUTIONARIES

In February 2017, the four engineers responsible for the creation of digital imaging sensors were awarded the Queen Elizabeth Prize for Engineering. Science writer and broadcaster Geoff Watts spoke to them about the development of the technology and how their contributions have revolutionised the way that visual information is captured and analysed.

The market for image-sensing technology is worth some $10 billion annually and could be half as large again by 2020

In selecting the winners of the 2017 Queen Elizabeth Prize for Engineering (QEPrize), the judges have managed to encompass four key stages in the history of solid-state image sensing that are embodied in four exceptional individuals. They are George Smith, who invented the charge-coupled device (CCD); Michael Tompsett, who exploited its potential in image sensing; Nobukazu Teranishi, who came up with the modern pinned photodiode (PPD); and Eric Fossum, who developed the complementary metal-oxide semiconductor (CMOS) sensor. These interlocking developments have had an impact to match the extent of their begetters' ingenuity. Image sensing has proved to be a technology as socially influential as it is fast moving.

"Any sufficiently advanced technology is indistinguishable from magic," wrote science-fiction novelist Sir Arthur C Clarke CBE. He was teasing us, but in this context, his wit has a double relevance. While most users of traditional film cameras had at least a dim idea of how their instruments captured light, this is much less true of the billions who reap the benefits of digital imaging every day; and the images themselves, whether a picture of some far distant galaxy or the interior of the human gut, often have an emotional resonance that surely merits the term 'magical'?

THE FIRST DIGITAL PHOTOS

The story behind image-sensing technology begins with George Smith. In 1959, after graduating from the University of Chicago with a PhD in physics, he joined a department of Bell Telephone Laboratories headed by Canadian physicist Willard Boyle (deceased). In line with the topic of his PhD thesis, he continued to study semimetals such as arsenic, antimony and bismuth. He subsequently moved to another department at Bell titled Device Concepts. In 1969, it was here that he and Boyle invented the CCD.

Boyle and Smith's intention was to exploit the capacity of semiconducting materials to transfer charge along their surface from one storage site to the next. They reasoned that patterns of charge, created electronically on the surface of a CCD, could be used to store and transfer information of the kind required by computer memories. In fact, the CCD was soon to find its major use in a quite different sphere, but the importance of Boyle and Smith's invention was self-evident, and celebrated in 2009 when the pair received the Nobel Prize for Physics.

The real value of the CCD began to emerge with its change of role from memory storage to image sensing, which is attributable to the second of the 2017 QEPrize winners, Michael Tompsett. Born in the UK, he studied physics at the University of Cambridge and followed it up with a PhD in engineering. By the time he came to work on CCDs, he had already demonstrated his inventiveness. While employed by the then English Electric Valve Company, he devised the uncooled thermal-imaging television camera tube. However, by then the focus of his interests had already begun to change.

"Ideas were being floated about solid-state imagers," he recalls, "and that was something I wanted to work on." In 1969, his fascination took him to the best place to be for anyone with such an interest: Bell Telephone Laboratories. He quickly realised how Boyle and Smith's CCDs could be exploited for their capacity to capture images, and embarked on a quest to develop imaging systems that were

THE CAMERA IN A PILL

One of the great virtues of the new sensor technology lies in miniaturisation: in this instance, a camera small enough to swallow. Capsule endoscopy, as it is called, relies on a camera, an LED and a transmitter built into a pill of the size commonly used to deliver drugs or vitamins. As it moves through the stomach and the rest of the gut, its camera records images that can be transmitted to a recording device worn by the patient.

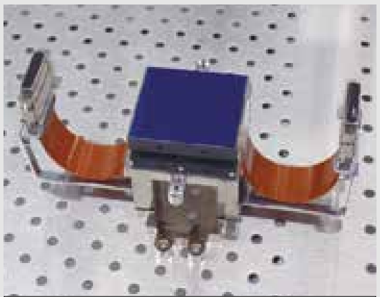
Conventional endoscopy relies on a long, flexible viewing tube inserted through the mouth and as far down the digestive tract as it will reach. Capsule endoscopy avoids the inevitable discomfort of this procedure, and dispenses with the need for trained staff to perform the examination.

A capsule camera may be tethered on a fine control wire and retrieved by pulling it back up after examination has been completed. However, as manufacturing costs fall, it can also be disposable and allowed to pass out of the body.

© GivenImaging

This is still a novel technology, and the extent of its benefits in searching for cancers or other abnormalities of the digestive tract is still being assessed, but findings so far are encouraging.

EXPLORING THE UNIVERSE



© European Space Agency

Euclid is a European Space Agency mission due to be launched in 2020. Its ambitious aim is to investigate the dark energy that accounts for three quarters of the energy/matter content of the universe, and may explain why the rate expansion of the universe is accelerating.

Crucial to the success of the mission are Euclid's reliable, lightweight, high-performance image sensors for observing the visible and near-infrared output of the billions of faint galaxies towards which they will be directed. The focal plane of the visible light instrument will comprise an array of 36 CCDs (as seen above) designed for the exceptional circumstances in which they will be operating. They are highly efficient, should be able to tolerate the radiation to which they will be exposed, and by generating 25 times as many pixel images as a top digital camera, should offer a far better quality image. Nothing less would allow astrophysicists to probe the history and nature of the universe.

much smaller than those in use at the time.

Image capturing by CCDs is a product of their response to light; when photons impinge on the light-sensitive surface of an array of pixels on a silicon chip, they trigger the formation of electrons. These are captured by the electrostatic forces in the pixel and accumulate. The brighter the light, the greater the number of electrons generated within any one pixel site. In an image brought to focus on the surface of a CCD, the location and number of electrons form an analogue representation of that image.

Besides acting as a photodetector, the pixel structure of a CCD also serves as a readout system. Charge generated in the pixels is transported, step-by-step, from one site to the next, across the array to one corner of the chip. Here, Tompsett added to the original CCD design with an analogue-to-digital converter to turn the amount of charge generated within each pixel into a digital value to be memorised. The digital readout so compiled forms a numerical description of the image. "I led the group that developed CCD images, and made the first colour camera," Tompsett says. "And I took the first colour pictures," he adds. "The first person to have a digital image taken of her was my wife."

IMPROVED QUALITY AND SMALLER

Tompsett had followed his father into engineering, and Nobukazu Teranishi also had a father who worked in the field. It was nuclear fusion that first attracted him, but that gave way to more basic physics and, when he joined the NEC Corporation in 1978, to image sensing. Photodiodes of that period were plagued by deficiencies such as noise and image lag, so Teranishi set out to unravel the roots of these problems and looked for a means of dealing with them. Two years after joining NEC, he invented the PPD.

Conventional photodiodes comprise a p–n (positive–negative) junction at the boundary between two types of the same semiconductor crystal. The 'n' side contains an excess of electrons, while the 'p' side contains an excess of holes. Teranishi added a p layer with a high level of impurities on top of the n layer of a normal photodiode. This modification had the effect of eliminating image lag, reducing dark current (the current generated even in the absence of light) and producing a much better image quality. It allowed pixel sizes to be reduced and their numbers increased, with a consequent boost to resolution. Mass production started in 1987, and a few years later, CMOS image sensors could also benefit from the use of PPDs.

Michael Tompsett holds a colour camera that he helped to develop while his wife Margaret holds a photo of herself, which was the first colour image using three solid-state imagers © Jason Alden

HANDS-FREE IMAGING TECHNOLOGY

In 2010, Microsoft released its motion-sensing device, Kinect. Kinect was an instant hit, selling more than eight million units in its first two months on sale and becoming the then fastest-selling consumer electronics device in history. Combining depth sensing and digital image sensors with machine learning, the gadget dropped gamers right into the action by turning their bodies into controllers.

At the time of its launch, Kinect's learning technology was so advanced that it earned the engineers behind it the 2011 MacRobert Award, marking it as the 'next big thing' in engineering. Although Microsoft announced in 2017 that it was ending production of Kinect, its groundbreaking technology lives on.

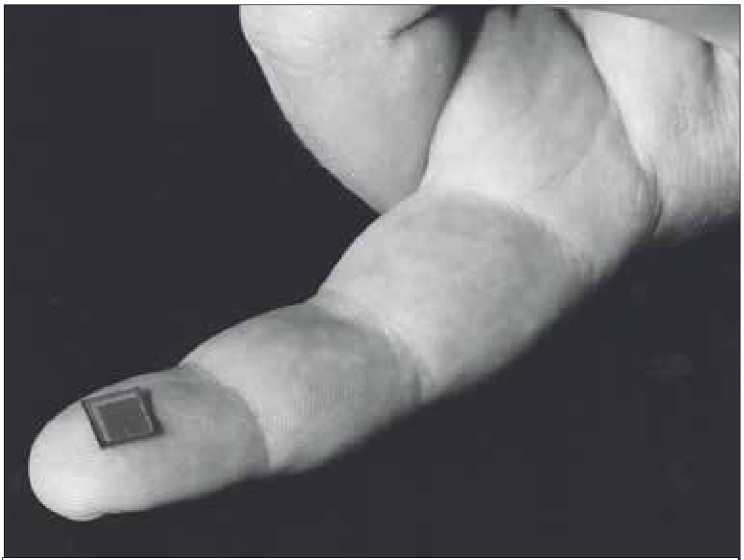
HoloLens, Microsoft's 'mixed reality' headset, incorporates depth-sensing technology and the latest in digital imaging sensors to capture the wearer's real-world environment. The device then places holograms directly onto physical objects within their field of vision to enhance reality.

© Microsoft HoloLens

Teranishi moved to the Panasonic Corporation in 2000, and subsequently to his present academic posts at the University of Hyogo and at Shizuoka University. Here he works on X-ray image sensors and photon counting sensors.

Eric Fossum too has moved between industry and academia. His introduction to image-sensing technology came while he was still in graduate school, shortly before CCDs began to find a widespread application in consumer products. Having worked on them at Columbia University in New York, he was recruited by NASA in 1990 and moved to its Jet Propulsion Laboratory (JPL) in California. By this time, CCD devices had proved successful in both their consumer and scientific applications, but NASA wanted smaller and less power-hungry CCDs that would also be more robust in a space environment. Fossum's remedy was to use CMOS microelectronics technology in developing a new generation of sensors.

Instead of transferring electric charges across the array of pixels and reading them at one corner, CMOS sensors use transistors within each pixel to amplify the voltage signal created there. As Fossum is at pains to point out, this is an idea that was first suggested in 1967 (before it could be implemented) by British engineer Peter Noble working at Plessey. CMOS sensors have most of the circuitry and components that they require integrated into the sensor itself (hence the term 'camera on a chip') and get by on as little as a hundredth of the power needed by CCDs. While the earliest CMOS devices performed relatively poorly by comparison with CCDs, they have been catching up ever since. CMOS devices are also cheaper to manufacture, and they eventually became the natural choice for small consumer electronic devices such as mobile phones.



CMOS sensors paved the way for smaller cameras and the development of the 'camera on a chip'. Although not as high quality as CCD sensors, they use less power and are cheaper to produce. They are also integrated into fingerprint recognition on smartphones and are used for identification in biometric passport booths for border control

Despite their advantages, early interest in the new CMOS sensors was, at best, lukewarm. Fossum left JPL in 1996 having already set up his own company, Photobit, to commercialise CMOS image-sensor technology. He has since returned to academic life and is now a professor at Dartmouth College's Thayer School of Engineering in New Hampshire. However, he is still engaged in entrepreneurial research; he and a former student have a created a new startup company called Gigajot. "We are working on a possible next generation image-sensing technology where we count each photon of light, one at a time," he says.

GLOBAL IMPACT

Returning to the present, upwards of 50 CMOS cameras are now being manufactured every second. The market for image-sensing technology is worth some $10 billion annually and could be half as large again by 2020. While nine out of every 10 sensors sold are now CMOS, CCDs are still preferred when the key requirements are for higher quality and greater light sensitivity. The ubiquity of sensing devices will become even greater as we surround ourselves with all sorts of new and digitally controlled machines and instruments that need to sense and respond to their environment.

Looking back, to what extent did the inventive minds of this year's QEPrize winners anticipate the impact of the technologies they had created? Pointing out that most families had film cameras, Teranishi was always confident that these would largely disappear. "What we really did not imagine was the invention of mobile phone cameras," he admits. It is these, of course, that have accounted for the explosive growth in the use of image-sensing devices.

Not without a hint of nostalgia, Tompsett points to the near total lack of effort or personal investment in the use modern imaging. "When you took pictures with a film camera you were careful," he says. "You were economical about it, deciding how you were going to take the picture, and where you were going to take if from, and so on, and then you would take just one picture." Now, of course, we take them by tens or even hundreds, scarcely thinking about it.

As for Fossum, he can still barely believe what has happened. As he says, "At the time [of developing the technology] I was thinking you could use sensors for this and sensors for that, and maybe they could become ubiquitous, but I did not really believe it would happen." However, it did "and it is truly astonishing".

RAISING ENGINEERING'S PROFILE

(Left): The three winners of the 2017 QEPrize take a selfie at the announcement in February 2017 © Jason Alden **(Right): Fourth winner, George Smith**

The Queen Elizabeth Prize for Engineering (QEPrize) is a global £1 million prize celebrating the world's greatest living engineers. Winners are selected by an international panel of judges and are responsible for a groundbreaking innovation that has benefitted humanity worldwide.

Alongside awarding the biennial prize, the QEPrize raises the public profile of engineering and inspires the next generation to take up the challenges of the future. Its Global Engineering Ambassadors' Network, a community of young, diverse role models from across the profession, promotes engineering excellence, while interactive initiatives such as the Create the Trophy competition invite young people to get involved and experience engineering for themselves. Bringing their ideas to life in a mobile and smartphone app, 14 to 24 year olds across the world competed to design the 3D-printed trophy that was presented to the QEPrize winners at Buckingham Palace.

CROWDSOURCED DISEASE DIAGNOSES

Small, cheap and universally available, digital image sensors have turned smartphones into the ultimate diagnostic tool. PlantVillage is a free, open-access platform that connects crop farmers with a global community of experts, diagnosing plant disease from the other side of the globe.

Farmers use their phones to take a photo as soon as they notice a change in their crops, uploading the image directly to an online database. With a worldwide network of scientists logging in, they can have an answer to their problem within hours. The rapid response allows farmers to quickly control the disease to save not only their own harvest, but others nearby.

The online platform was created by two assistant professors at Penn State University's College of Agricultural Sciences, and is getting smarter; it learns from an ever-growing image bank and can offer computerised diagnosis.

While still in its infancy, the artificial intelligence matches healthy and diseased leaves, and can so far detect 26 different diseases in 14 plants with 99% accuracy. Ultimately, farmers could receive a diagnosis within seconds of uploading images.

© Pixabay.com/Hans

ACCURATE TARGETING OF TUMOURS

The AlignRT system monitors the patient's surface area during radiotherapy treatment, using ceiling-mounted stereoscopic cameras. This allows the patient to be positioned accurately and tracks for any movement during radiation therapy

Radiotherapy is a widely used treatment for cancer, allowing doctors to shrink tumours that cannot be surgically removed because of their size. However, there is a risk of damage to healthy tissue from radiation beams if the patient moves. Science writer Tereza Pultarova talked to Norman Smith from Vision RT, a finalist for the 2017 MacRobert Award, about its technology that accurately tracks a patient's position before and during treatment.

In the UK, one in every two people are likely to receive a cancer diagnosis at some point in their lives, and about 50% of them will require radiation therapy, which often successfully cures patients.

Radiotherapy works by targeting high-energy photon beams into tumours to destroy cancer cells. However, the radiation can also be harmful to healthy tissue, so healthcare professionals do their utmost to ensure that only the target area receives the dose. However, slight movements that patients naturally make during treatment can be almost impossible to detect, and these can lead to radiation damage to healthy tissue and potential long-term health problems.

Generally, in radiotherapy treatment, laser beams are used to help position the patient's body before the treatment begins. Since several radiotherapy fractions (a series of treatment sessions that make up the entire course) are usually spread over a number of weeks, repeated accurate positioning is needed. To aid this, the patient is often given tattoo marks in several places so that the radiotherapist can determine the exact location of the tumour inside the body, based on a previously taken CT (computerised tomography) scan.

In order to ensure that patients can be set up precisely and radiotherapy is delivered as accurately as possible, technology company Vision RT developed AlignRT, a completely non-contact system that continuously tracks the patient's position in 3D before and during treatment with better than one millimetre accuracy.

A pseudorandom pattern is projected onto the patient's body, which is picked up by the cameras and used to develop a 3D image of the patient's surface area to precisely calculate their location during treatment

CREATING A SYSTEM

After graduating in electrical engineering from the University of Cambridge and completing a PhD in medical image processing at Imperial College London, Norman Smith, CEO of Vision RT, joined a startup that was developing stereoscopic imaging techniques for various applications. Stereoscopic imaging systems mimic human visual perception to see surroundings in three dimensions; they consist of two cameras positioned at a known distance from each other, in the same way that humans have two eyes to perceive depth.

During this period, Smith visited a few radiotherapy clinics and was surprised at how primitive some of the techniques for setup and monitoring were. He was confident that stereoscopic technology would be able to monitor not just a few tattoo marks, but the entire patient before and during radiotherapy treatment, and would also remove the need for the tattoo reference points on the body, which can remain a permanent reminder for patients of their cancer. While it was here that the idea for the AlignRT technology was born, the company that Smith worked for was not interested in developing the idea further.

In 2001, Smith and co-founder and CTO Ivan Meir began operating as Vision RT from the attic of Smith's parents-in-law's house in North London. Gideon Hale, Vice-President Operations, joined the organisation 18 months later. The journey from vision to reality was not straightforward; at the time, there were no suitable 'off-the-shelf' stereoscopic camera systems available so they designed and engineered their own proprietary cameras, electronic hardware, processing software and user interface. Apart from the camera chips and lenses, all the system's components are manufactured in the UK.

The system continuously monitors the patient surface using three separate 3D camera modules that are ceiling-mounted in the radiotherapy treatment room and view the treatment table from different angles. The camera modules also contain a projector that illuminates the patient's body with a pseudorandom pattern on the surface of their body. This pattern is detected by the cameras and custom-written stereo-matching software to find corresponding points between pairs of calibrated stereo camera images. Through the process of triangulation, 3D coordinates are calculated for each set of 2D image points, which results in a 3D surface model comprising tens of thousands of points. The data from all 3D cameras is combined and the surface position is determined to sub-millimetric accuracy at a rate of 2 to 10 hertz (Hz) to precisely define the location of the patient as they undergo radiotherapy. This accurate surface map is then dynamically matched to a reference surface model derived from a CT image, and treatment is planned using this. This allows the location of the tumour, based on the patient's body surface, to be tracked in all six degrees of freedom (the freedom of movement of a rigid body in a three-dimensional space) to ensure that the treatment is being delivered correctly.

ACCURACY, EASE AND COMFORT

In addition to real-time 3D mapping of the surface, the company has developed an easy-to-use interface software that, via a simple colour bar display, gives directions that allow the radiotherapy operator to position the patient faster and more accurately. Moreover, instead of relying on a human operator to stop the beam manually if

Each of the ceiling-mounted modules contain a projector and stereoscopic camera. These need to be precisely aligned and rigid

the patient unexpectedly moves, the system senses the smallest of movements from the patient and automatically pauses radiation delivery, preventing damage to healthy tissue. A further benefit of this development is that it also removes the need for the patient to be held in place by a variety of invasive immobilisation frames or moulds, which were previously often used to restrict patient movement. Historically, treatment staff would also monitor the patient's position and observe the tattooed marks via closed-circuit television from a neighbouring room. If the patient moved, they would manually stop the radiation beam, but this method is unable to pick up small movements and requires constant vigilance.

Accurate surface mapping requires the camera positions to be precisely aligned and rigid. This is helped by the fact that radiotherapy treatment rooms are usually solid concrete-walled and roofed structures, but it also means that the camera/projector modules must be rigid and thermally stable, which can be very difficult to achieve with an optical measurement system. The company solved this through careful mechanical design and an innovative thermal management solution, which ensures that the modules are operated at a controlled temperature.

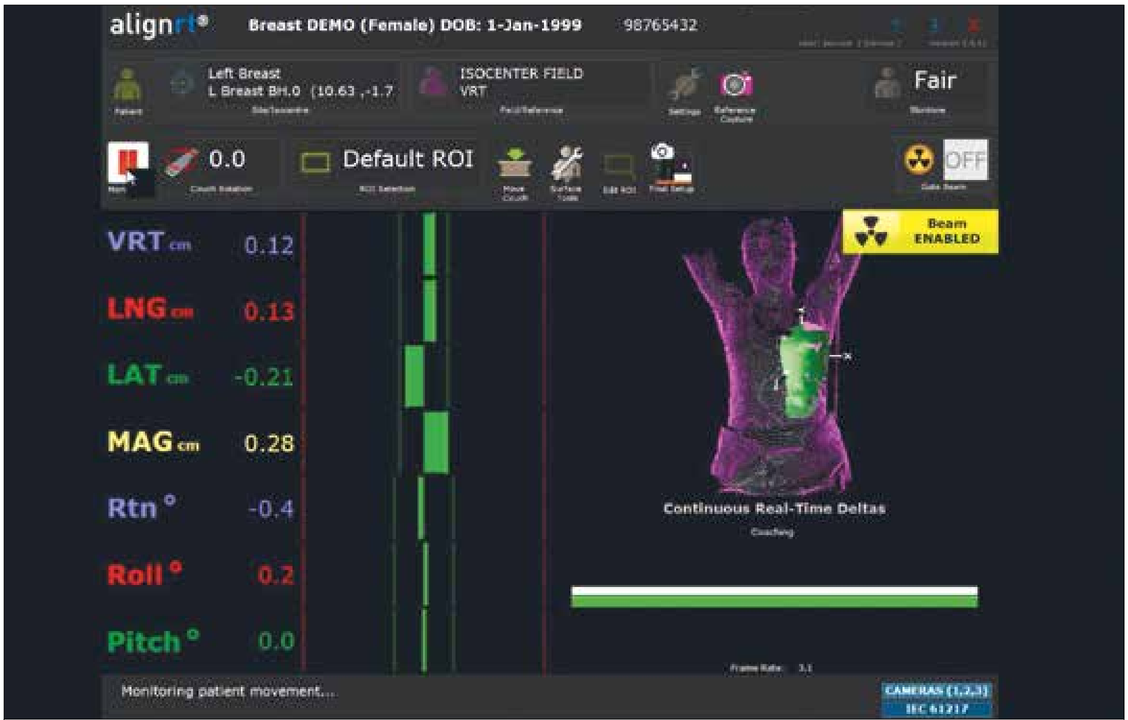
Any detected motion must be synchronised to the treatment delivery machine (the linear accelerator), so the company has designed its own electronics modules for this and interfaced these, in collaboration with the different manufacturers, to their radiotherapy treatment delivery machines. The processing software, which at its core uses a mathematically complex and computationally challenging matching technique, must be both fast and accurate over the whole image to track any patient movement at high frame rates. The whole system calibration is checked daily and to do this the company has designed easy-to-use calibration phantoms that are mounted on the treatment couch, with built-in hardware and software consistency checks.

CONFIRMED RESULTS

The company's first prototype was tested at the Royal Marsden Hospital, a cancer specialist centre, in 2002. This confirmed that the system could track an object to within a millimetre, and the following year, Vision RT submitted its data to the American Society of Radiation Therapy and Oncology (ASTRO), the world's largest professional radiotherapy organisation. On acceptance of its paper for oral presentation, the company decided to attend ASTRO 2003 to exhibit its prototype technology at the associated industry trade show.

A chance encounter at the event between Smith and Meir and Dr George Chen, a professor at the Department of Radiation Oncology at Harvard Medical School and a leading authority in the field, initiated a productive relationship. Dr Chen had been attempting to develop something similar with MIT for three years, but had been unsuccessful. Within a year, Vision RT had installed a prototype system at Massachusetts General Hospital, Harvard Medical School's largest teaching hospital and one of the world's leading biomedical research facilities.

By 2005, two scientific papers were published in peer-reviewed journals; soon after, the company received clearance to market the technology in the US and the first units were sold, initially to leading academic institutions that were focused more on technical efficacy than usability. As Vision RT's market expanded, feedback from more routine users complaining about the ergonomics of the system required the engineers to completely redesign the system's user interface to make it very easy to operate. During subsequent years, a new and improved camera/projector system was developed, as well as an enhanced calibration technique to enable the exceptional accuracy that is required for radiosurgery treatment where the radiation beam is both narrower and of significantly higher intensity.



The software aids healthcare professionals in rapid positioning of patients prior to radiotherapy, and highlights any movement they make from their intended position during treatment

EXPLORING NEW AREAS

Vision RT long ago left behind the cramped attic of Smith's parents-in-law's home and its team of five has expanded to more than 150 people. Now, the technology is used in 70% of the top 50 cancer centres in the USA and in more than 30 countries around the world. The system is becoming a standard in radiotherapy treatment. The company has pioneered a new field of surface-guided radiotherapy treatment (SGRT) and has built up and supported a 'SGRT community', consisting of almost 1,000 healthcare professionals, which trains, shares and helps develop the technique and the AlignRT product.

The company has also signed a distribution agreement with Varian Medical Systems, the world's largest manufacturer of radiotherapy treatment delivery systems, through which a Varian-branded version of the AlignRT 3D surface-imaging technology has become part of the company's offering; it is incorporated into many of Varian's radiotherapy systems.

The accuracy and rapid mapping of the system has enabled an advanced form of treatment for left-breast tumours. Because of the closeness of the heart to these tumours, damage to cardiac blood supply is a common complication. However, if the patient takes a deep breath, this moves the heart away from the chest wall. By monitoring when the patient is holding their breath, the AlignRT technique can ensure that the radiation is only delivered to the tumour during this period and not to the heart. Using the simple alignment software that had already been designed to enable the radiographer to position the patient, Vision RT has produced a simple tablet-based bar graph display that the patient can use to ensure that they have taken a deep enough breath to move the chest wall, and hence the tumour and heart, into the right position for treatment.

The treatment of left-breast cancer has been a success story; a recent clinical study in North Carolina showed that no 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.

With Vision RT having over 50 patents to date and its clinical evidence being evidenced in more than 60 peer-reviewed papers, it seems that the practice of SGRT can only go from strength to strength.

BIOGRAPHY

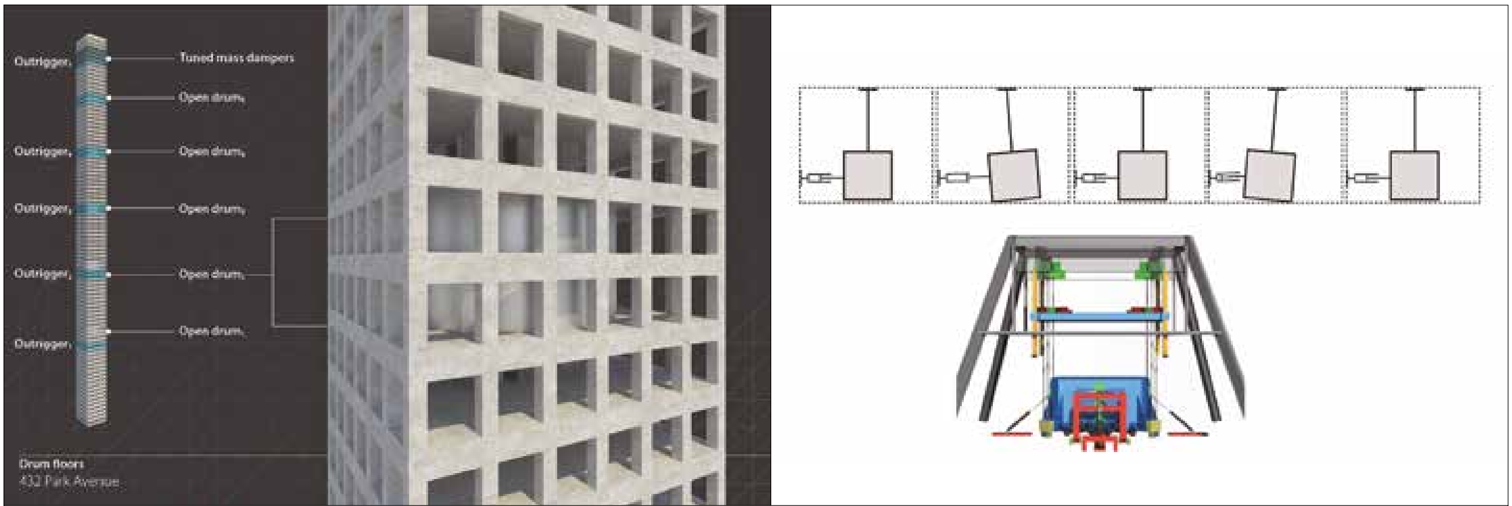
Dr Norman Smith is CEO and co-founder of Vision RT. He studied engineering at the University of Cambridge and holds an MSc and PhD in medical imaging from Imperial College London. Dr Smith is a Fellow of the Institution of Engineering and Technology, and is named inventor on several patents.

The author would also like to thank Professor David Delpy CBE FREng FRS for his help in putting together this article.

THE SKY'S THE LIMIT

432 Park Avenue is one of the most recent additions to the New York City skyline. The building stands at 426.5 metres (86 storeys) high. At about every 12th storey, the building has been left windowless and 'open' floors have been created, to reduce vibration in windy conditions © Nicola Evans

Tall buildings are rising in cities all over the world, at a rate and with a variety never seen before. Engineer and writer Hugh Ferguson talked to skyscraper designer and London-based structural engineer Kamran Moazami, about one of New York's most recent skyscrapers – 432 Park Avenue – and the engineering challenges of designing tall buildings.



(Left): The square-shaped concrete core of the building is connected by 'outriggers' (double-storey concrete frames) to the exterior girder-column grid at roughly every 12th floor so that they act monolithically and increase the overall lateral stiffness. (Right): Two mass-tuned dampers were also added to the top of the building to control its movement. A tuned-mass damper is a mass that is supported by a pendulum arrangement and connected to the structure by means of springs and/or dampers

In the heart of Manhattan, where land values are among the highest in the world, stands 432 Park Avenue, one of New York City's newest skyscrapers and a towering example of what new engineering techniques, combined with high-performance materials, can achieve.

New York was the birthplace of the skyscraper, notably with the Chrysler Building and Empire State Building in the early 1930s, both of which are steel-frame buildings of rectilinear shapes. In the 1960s, the skyscraper had something of a resurgence with the introduction of tubes (usually in steel) for perimeter and interior columns and perimeter diagonal bracing, which greatly reduced the weight of steel required and hence the cost. Many buildings over 40 storeys that have been constructed since the 1960s use a tube system adapted from the structural engineering principles of Bangladeshi-American structural engineer Fazlur Khan. This included the John Hancock Center in Chicago, and the World Trade Center twin towers in New York (1973).

Tall buildings continue to spring up throughout the world in response to many factors, such as increasing urbanisation, a desire to create iconic buildings, and the discovery that people across the world love grand views. Now, more than half of the world's 20 tallest buildings are in China (with four elsewhere in the Far East, three in the USA and two in the Middle East). Before 2000, two thirds of skyscrapers were commercial: since then, more than two-thirds have been residential or mixed-use.

SLENDER AND STABLE

At 426.5 metres, 432 Park Avenue is one of the world's 20 tallest buildings. It is the second tallest building in New York City and the third tallest in the USA. The building is entirely residential and currently stands as the tallest residential tower in the Western Hemisphere. However, much more significantly, with its compact 28.5 metre-square footprint, it has an aspect ratio (height/width) of 15:1, a slenderness that would have been unthinkable a decade ago. This has helped the developer to gain more usable space out of a comparatively small plot, and to give the residents unrivalled views of the Manhattan skyline. It also presented interesting challenges for the building's engineers.

432 Park Avenue had to be designed to transfer its own weight down to the foundations, to resist seismic and wind loads, and – most challenging of all with such a slender building – to manage the movement of the building under wind loading so that no movement would be detectable. All tall buildings move in the wind, but occupants, particularly residents, do not want to feel the sway. That meant keeping the lateral acceleration of the building (its movement in wind) below around 0.1 m/s2 (metre per second squared) in a 'once-in-a-year' gale.

On most tall buildings, extensive wind tunnel testing is an integral part of the structural analysis and design. This may include: high-frequency force balance tests; multi-degree of freedom aeroelastic modelling, which explores the independently acting factors that influence the interaction between inertial, elastic, and aerodynamic forces that occur when the building is exposed to wind; wind studies done at large scale on just one section of the building at a time; cladding pressure and wind studies to ensure that cladding panels, windows and fixings will not be blown off in a gale; pedestrian-level comfort testing, to ensure downdraft wind on the building and any street-level wind tunneling does not create discomfort for nearby pedestrians; and wind-induced aeroacoustic studies, to check and ensure that wind will not cause any whistling or noise-generated issues.

At the time, 432 Park Avenue was one of the most slender buildings in the world, designed by engineering consultant WSP. Therefore, wind-related testing was particularly rigorous, with

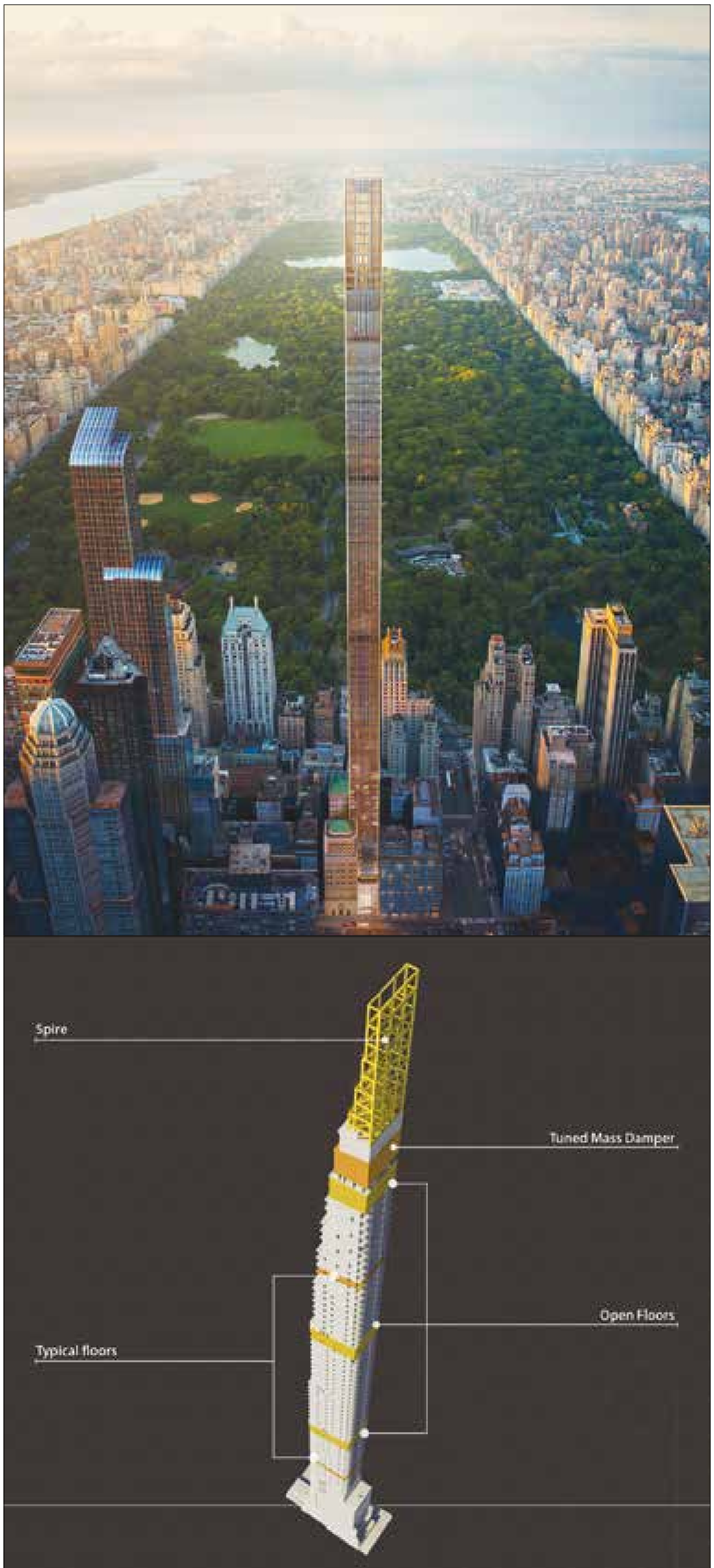
On most tall buildings, extensive wind tunnel testing is an integral part of the structural analysis and design

around five force-balance tests backed up by several all-day workshops to establish the optimum configuration, followed by a few aeroelastic tests on the final design.

First, the building had to be made as stiff as possible to resist overall bending, while still leaving large, open areas on the floor plan for attractive living spaces. This was achieved by creating a 9 metre by 9 metre concrete shear-wall core around the lift shafts, which formed the building's central spine. Less conventionally, the strong core was supplemented by a framework of concrete columns and spandrel beams forming the building envelope and avoiding the need for externally mounted cladding. Cast-in-situ floors span between the central core and the perimeter frames. To ensure that the concrete perimeter framing and interior core respond monolithically to structural demands, they were connected by massive double-storey concrete frames, known as 'outriggers', which were concealed in the plant rooms at about every 12th floor.

Despite its lateral stiffness, the tower still tended to move unacceptably in varying wind conditions, and the lateral-load-carrying system had to be 'tuned' to minimise displacement, acceleration and vibration. This was solved by adding mass to the upper levels, achieved by increasing the typical 250-millimetre thickness of the concrete floors to 450 millimetres. Two 650 tonne mass-tuned dampers were also added to the top of the building: these are large steel weights supported by cables as pendulums and connected laterally to the structure by viscous dampers, which absorb the energy of the moving weights and transfer the associated forces into the building structure, slowing the building's acceleration to acceptable limits.

Early wind tunnel testing had shown that the building exhibited significant 'vortex shedding', which is an oscillating airflow phenomenon that can occur when wind flows past a building at certain velocities. Vortices are formed at the back of the building, detaching periodically from either side. Each low-pressure vortex tends to pull the building towards the centre of the vortex, so the effect can be to induce vibration, particularly if the frequency of vortex shedding approaches the resonant frequency of the structure. The solution at 432 Park Avenue was ingenious and innovative: by leaving the building windowless at precise levels and creating 'open' floors – a technique comparable to making



(Top): A rendering of 111 West 57th Street. Its aspect ratio of 24:1 will make it the world's most slender building. (Bottom): Shear walls run the full length of the east and west exteriors and have been thickened to as much as one metre. Like 432 Park Avenue, it also has open floors that the wind will pass through to reduce vibration

holes in the sail of a boat – the wind loading was reduced and so was the vortex shedding. Conveniently, these levels could be designed to coincide with the plant rooms, and to some extent the outriggers, at about every 12th floor.

Although these 'open' floors take up valuable floor space, this is more than compensated for by the additional stability that allowed the height of the building to be increased to 86 storeys.

The concrete required for the building was no ordinary concrete. For the lower sections carrying larger vertical and lateral loads, it had to have a specified compressive strength of more than 100 MPa ('high strength' concrete is considered to have a compressive strength of 50 MPa or more). All structural concrete was designed for enhanced durability by minimising air content and the water/cementitious materials ratio, and with a higher-than-normal modulus of elasticity to minimise deformation. To aid placing and to improve the finished appearance, it had to be able to be pumped to great heights. Since there was to be no cladding to cover potential blemishes on the exterior of the building, architectural exposed concrete was specified in an attractive white colour and was placed with near-perfect workmanship. Although the exterior concrete should be maintenance-free, the exterior of the building required access for glass cleaning and replacement, which will be done using a telescopic building maintenance unit (BMU) mounted on the roof.

EVEN TALLER TOWERS

Now, just three blocks away, 432 Park Avenue's successor is nearing completion. Not content with an aspect ratio of 15:1, 111 West 57th Street has a ratio of 24:1, which will make it the world's most slender building. At 438 metres, it is slightly taller than its neighbour and shares many features: both are high-end residential buildings, both use high-strength concrete, and both have a tuned mass damper on the top and gaps allowing the wind to pass through to minimise vortex shedding.

The main difference is that the architect and developer for the latter wanted clear, unobstructed views northwards over Central Park and south towards Lower Manhattan. The solution was a concrete core, linked to two concrete shear walls (a structural system composed of braced panels) running the height of the building on the east and west sides and allowing clear views north and south, so that the overall structure resembles a giant cantilevered concrete I-beam standing on its end. The tower is slightly tapered, and the external walls will be clad in terracotta and bronze rather than architecturally exposed concrete. Even more slender buildings are now being planned, although an aspect ratio of 24:1 is approaching the limit of what is currently feasible.

EVOLUTION OF SKYSCRAPERS

The buildings at 432 Park Avenue and 111 West 57th Street are responding to the specific parameters of the New York City market, including strong demand for high-end residential properties with outstanding views, and locally available high-strength coarse aggregates needed for making ultra-high-strength concrete (a similar compressive strength in London, for example, would require imported aggregate, and is therefore a much more expensive concrete). In different parts of the globe, the parameters or constraints are likely to be different and so too are the solutions.

The original rectilinear steel buildings most usually associated with skyscrapers have largely been succeeded by concrete or composite concrete-and-steel, and the equally ubiquitous office buildings have given way to varieties of mixed-use towers: modern skyscrapers are

SAFER SKYSCRAPERS

Skyscrapers are now among some of the safest buildings in the world, if only because they must be thoroughly engineered to the finest detail, and not just for structural safety. For example, the fixings of every external cladding panel should allow for sufficient movement to accommodate the building's sway under anticipated conditions.

Most modern tall buildings have a fire strategy, which covers such issues as means of escape, detection and alarm, fire suppression, smoke control, firefighter access and facilities, compartmentation, and internal and external spread of fire. Most high-rises now include dedicated fire stairs and some have lifts that can be used for fire escape, which require special details such as pressurised lobbies where people can wait for the lifts and an independent cooling system for the lift motor room. The main fire element of tall building design is ensuring that compartmentation is maintained until the fire is exhausted or controlled. Spread of fire on the exterior of a building is usually mitigated by choosing insulation materials of limited combustibility, provision of adequate fire-stopping, cavity barriers around openings, and main compartmentation lines. For example, in August 2016, a fire burned dramatically for two hours on the outside of Dubai's 84-storey Torch Tower, where some of the cladding systems were not of limited combustibility and fire-stopping was inadequate. Despite this, other elements of the fire strategy worked well, particularly suppression that ensured safe escape for occupants, and consequently there were no casualties.

THE ENGINEERING CHALLENGES OF TALL BUILDINGS

The Shard

Completed in 2012, the Shard is London and the UK's tallest building at 310 metres and 95 storeys ('Building the Shard' *Ingenia* 52). It is shaped as an irregular pyramid with highly complex geometry. The Shard is a modern mixed-use tall building with retail at the base, offices in the lower levels, a hotel in the middle and residential near the top. A strong central concrete core and a hat truss that engages all perimeter columns form the spine of the building, and the remainder varies with use: structural steel was the optimum solution for the offices, where deep steel beams could allow plenty of space for the extensive services required. For the hotel and flats, where acoustic separation was more important and where spans were shorter owing to the tapering of the building, concrete floors were preferred, which were thinner so that two extra storeys could be added within the same overall building height. The tower then reverts to steel for the viewing gallery and the spire.

Newfoundland

The 220-metre high, 60-floor Newfoundland residential tower in Canary Wharf, London, straddles the Jubilee Line tube tunnels, which are close to the surface at the tower's location. This required careful piling between and beside the tunnels, as well as a major load-transfer structure to connect the building's loads with the piles. However, to avoid disturbance to the tunnels, it was necessary to keep the weight of the building to a minimum. The solution was a 'diagrid' of diagonally placed steel members on the outside of the building creating a diamond pattern, and the use of post-tensioned concrete floor slabs connecting the diagrid to the concrete core. The diagrid was so light and strong that the thickness (and therefore the weight) of the shear walls in the concrete core could be reduced to just 300 millimetres.

Torre Mayor

The 225-metre high, 55-storey Torre Mayor in Mexico City was Latin America's tallest building when it opened in 2003 and is now Mexico's fourth tallest. The design priority for this building was seismic design, as it stands in the lakebed area where the heaviest damage from the catastrophic Michoacán 1985 earthquake was recorded. Designed to resist an 8.5 Richter earthquake, Torre Mayor has an arrangement of 96 viscous fluid dampers (with technology borrowed from the shock-absorbers of a car) attached to the diagonal cross-bracing on the perimeter of the building, which safely absorb the earthquake's energy. A 7.6 Richter earthquake in 2003 did no damage: indeed, the occupants did not even notice that a tremor had taken place. The structure also responded as expected when the 7.1-magnitude earthquake of Axochiapan occured in September 2017.

22 Bishopsgate

When it is completed in 2019, 22 Bishopsgate will be London's second tallest building at 278 metres with 62 floors. This will be even more of a 'vertical village' including retail, restaurants, an auditorium, various leisure facilities, including a climbing wall on the 25th floor, and offices. It will be the first building in the UK to be accredited for standards to improve building users' health and wellbeing. The main challenge here was to address what had gone before: a previous scheme was abandoned in 2012 because of the recession, with just the foundations and seven storeys of the core constructed. The core was deconstructed, but for the new tower to be economical, a way had to be found to place an entirely different building on the existing foundations (including London's deepest piles). This required elaborate analysis and design at the base of the building to transfer the loads to the foundations such that the full strength of the existing piles was mobilised, but no individual pile was overloaded.

becoming self-contained cities in the sky with a mix of residences, offices, hotels, restaurants and public areas.

As ever-stronger materials are developed, there is no structural limit to how high skyscrapers could be built. The only foreseeable limits are likely to be the larger footprints required at ground level and the transport links to service the many occupants, for example the constraints of providing fast and efficient vertical transportation, and economic viability: larger buildings cost more, take longer to build, and take longer to let, so developers need even deeper pockets. However, with increased urbanisation, a public appetite for tall buildings and the ingenuity of engineers, the surge in skyscrapers worldwide is set to increase still further – and some of them will be even taller.

BIOGRAPHY

Kamran Moazami is Managing Director, Property and Buildings, at WSP. He studied structural engineering at Columbia University in New York. After obtaining his master's degree, he joined New York skyscraper firm, Cantor Seinuk, where he worked on several high-rise buildings. In 1996, he relocated to the UK to head up the company's London office. Later on, Cantor Seinuk was acquired by London-based firm WSP.

Hugh Ferguson also talked to Nick Offer, Head of London Building Services for WSP.

All projects mentioned in this article have been structurally designed by WSP

A TALENT FOR BURSTING BUBBLES

Professor Timothy Leighton FREng FRS, Professor of Ultrasonics and Underwater Acoustics at the University of Southampton

Creatures of all sizes, from bacteria to whales, have shaped the career of Professor Timothy Leighton FREng FRS, but it all started in a babbling brook, where he began to research the physics of sound in water. As he explained to Michael Kenward OBE, his research changed direction when an invention to clean medical devices brought him into the challenging world of antimicrobial and antibiotic resistance.

A typical research career seemed likely for Professor Timothy Leighton FREng FRS when he was studying undergraduate physics at the University of Cambridge. He was interested in astrophysics and cosmology, but felt the urge to get into the laboratory. "There was a part of me that wanted to feel something real between my hands," he explains. Instead of diving into an undergraduate project that needed impressive equipment, molecular beam epitaxy for example, he chose an area that was, as he puts it, "an acorn that could turn into an oak tree". His attention turned to underwater acoustics, such as what creates the sound of a babbling brook. It kick-started a career investigating the physics of sound in liquids.

Professor Leighton wanted to continue in the same area when it came to a PhD project. Underwater acoustics might not have been mainstream research at the Cavendish Laboratory (Cambridge's physics department) at the time, but it had the limited amount of equipment he needed to carry out high-speed photography, for example. He received backing from a visiting academic that helped to convince a professor so that he could continue studying the physics of bubbles in liquids. "It amused him as a strange offshoot," adds Professor Leighton.

The undergraduate project had focused on how gas bubbles trapped by breaking waves or a waterfall make a sound. For his PhD, Leighton reversed the process; rather than listening to what came out of a fluid, he set out to research what happened when he injected sound into it. In particular, he set out to research what happens when sound enters the womb to scan foetuses, an issue that raised safety issues as the foetus is a delicate tissue. "Any mechanical system that makes a sound will vibrate if you shoot sound at it close to its natural frequency," he says. "The megahertz frequencies needed to get nice spatial resolution in images would resonate with microscopic bubbles, which feasibly you might have in the body. Nobody knew at the time." Thus, began a research career that applies physics in real-world applications.

Professor Leighton completed his PhD and some follow-up work, which gave him early exposure to something that became increasingly important in his research. "It helped me to get an all-round picture of the different environments that people work in." His research generated close links with the local hospital, and he came to understand the relationship between clinicians and medical physicists. Professor Leighton realised that the equations at the heart of his work would have little impact on anyone without an understanding of those relationships, the limitations and the environment people were in.

His first papers appeared amid debates about the safety of ultrasound in foetal monitoring. "The ultrasound images back in the seventies were black and white and grainy. It was hard to see anything. If you look at today's images, they are brilliant." The work elicited an invitation from the World Federation for Ultrasound in Medicine and Biology to join a working party on the guidelines for safe foetus scanning. "I popped off to Japan, where people from many countries, industry and academia, and the healthcare sector got together and thrashed through the various hazards. I was by far the youngest there, so incredibly lucky and grateful to be given an unparalleled opportunity to work with the pioneers whose papers I had been reading," he adds. The working party came about because there was growing interest in the safety of ultrasound scanning, especially in the USA. Medics wanted ever more detailed images but that meant pushing up the sound frequency. Scanner makers could deliver that, but higher frequencies are more strongly absorbed and that means greater heating, which could increase the risk of damage to the foetus. The working group set out to provide answers on safety. As Professor Leighton describes the process: "It was basically about coming to a resolution, while being wise enough to take into account the big picture, which I thought was engineering.

"It was based on rigorous maths, careful experimentation, considering the social, economic and ethical dimensions, and coming up with a set of guidelines that I am very proud of." The effect was widespread. "Since then, two billion children have been scanned under these guidelines.

"Over the years, the power output of these machines was going up and up and up at a huge rate. I think the scientific community did a good job of putting a line in the sand and saying 'These are the hazards. This is how you would calculate them'."

One outcome of the guidelines was the development of onscreen displays on all scanners that showed the likelihood of various hazards to the foetus for the settings in use, which allowed operators to judge possible risks. "There are a couple of numbers shown on the screen. They don't say 'You can't exceed this'. They advise the clinician of the likelihood of a problem, so the clinician would know that, if what they are doing is lifesaving, disregard those numbers – they are a lower priority than the medical procedure. But if the procedure is routine, you should not exceed those numbers."

PROBLEM SOLVER

Professor Leighton's work on foetal scanning set the pattern for his career; he wanted to have positive effects on people's lives. In 1992, this thinking guided his research when he moved to what is now the Faculty of Engineering and the Environment at

Professor Leighton was inspired to invent TWIPS (twin inverted pulse sonar), and from there TWIPR (twin inverted pulse radar), with colleague Paul White after watching dolphins hunting with bubble nets. He also saw dolphins blowing and playing with bubble rings (whether this is for recreation or education is not known) and decided to solve the problem of how they did this while he was in a swimming pool when on holiday in Menorca

the University of Southampton to join the Institute of Sound and Vibration Research. Writing papers was not enough; although his tally is now well over 400 publications, studying the physics of sound underwater fuelled his engineer's desire to create technologies that would solve problems. For example, collaboration with a team from the National Oceanography Centre in Southampton produced GeoChirp 3D, the first truly three-dimensional sub-seabed profiler (a way of looking at what is under the seabed). The technology was used to image the skeleton of *The Invincible*, a Royal Navy ship that sank in the Solent in 1758. That research has yielded equipment for conducting sonar surveys of the seabed, in marine archaeology and geology, such as researching landslides in Norwegian fjords. In a different domain, Professor Leighton's team has developed sensors for the US Department of Energy's neutron-scattering facility.

Back in the medical world, Professor Leighton's problem-solving helped to develop needle-free injectors to treat migraines, as well as LithoCheck, an ultrasound 'smart stethoscope', developed with Guy's and St Thomas' NHS Foundation Trust, to predict what is going on when doctors use ultrasound, or shock-wave lithotripsy, to treat kidney stones. The idea is to tell doctors when treatment has succeeded and to prevent over exposure to ultrasound and the risk of damaging healthy tissues.

The natural world was also an obvious subject. Professor Leighton's research has taken in whale sounds, dolphins, fish and bubbles in surf. "We were the first people to measure the bubble population in the surf – how the oceans breathe," he says. He was also the first to propose how humpback whales get together to produce 'walls of sound', bubble nets, to catch prey. Rather than being purely a zoologist's problem, Professor Leighton says that this is an engineering issue; as is the maths that dolphins use in their heads when they are processing signals. He concluded what that maths was, and so devised the world's only sonars (twin inverted pulse sonar and biased pulse summation sonar) that can detect mines in bubbly seawater.

PUBLIC ENGAGEMENT

Research into these areas aroused media attention and fuelled Professor Leighton's enthusiasm for public engagement. "I am very committed to public engagement. I get a big kick out of it, whether it is with five-year-olds or people who are double my age." His public engagement activity has included time as a member of the Royal Academy of Engineering's *Ingenious* panel. He believes that the scheme, which awards grants up to £30,000 for public engagement activities to promote engineering, appears to be working well and has raised the bar enormously. "Ten years ago you could propose something that would easily have got funded, that would not stand a chance today. If you thought 'I am going to impress the kids with 3D printers, I'm going to produce a movie and put it on YouTube', forget it. That is not enough." The goalposts have moved. "Ten years ago we were asking academics and engineers just to get interested in talking to the public. However, today public engagement cannot be a one-way process, with engineers passing on their 'wisdom'," he says. "It is about creating meaningful dialogues and not simply talking at people. You should be finding out what is in their hearts and minds. You should be a person with a watering can, nurturing any seeds you find, helping them to grow, giving your full attention to the person in front of you."

Public engagement has been important in Professor Leighton's latest venture, which has taken him in an unexpected direction. He has set himself no less a task than trying to overcome the problem of antimicrobial resistance (AMR). The medical world talks in terms of an 'antibiotic apocalypse', the notion that sometime soon, perhaps around 2050, so many bacteria will have evolved that can resist all known antibiotics that AMR could be killing more people than cancer.

AGAINST RESISTANCE

Chemists and the pharmaceuticals industry see new antibiotics as the solution to AMR, but Professor Leighton has other ideas. "I could see that there was a disconnect between the size of the problem and the way that we were thinking about it," he explains. Bacteria will develop resistance to new antibiotics. Why not take advantage of a technology that does not change the gene pool of the bugs? "The mindset of the community has to change before they start seeing that there are other potential solutions."

Professor Leighton's move into AMR started when he tried to persuade the community to change that mindset. He wanted the medical world to consider using ultrasound to clean wounds, avoiding the antibiotic treatments that, through natural selection, contribute to the development of antibiotic resistance in bacteria. He even had an invention that could take on the task, a device that came out of what he calls his 'toy

Professor Leighton and members of his team demonstrate StarStream to Professor Dame Sally Davies DBE FRS, Chief Medical Officer for England. An obvious application of this ultrasonic cleaning technology is in cleaning medical and dental instruments. Sold as StarStream, a company now has a licence to produce ultrasonic cleaners for just this purpose © Mengyang Zhu

factory'. In reality, the factory is a cramped basement laboratory, filled with instruments and plumbing, where Professor Leighton's small research team works on a series of inventions that use ultrasound. One of these, StarStream, looks like a small hairdryer, but dispenses a stream of room-temperature water instead of hot air. He demonstrates the device by smearing a spanner with eye liner. Aim the device's water stream at the smear and nothing happens. Flick a switch and the water becomes cloudy as an ultrasonic transducer injects bubbles into the stream. The eyeliner instantly disappears, even from the nooks and crannies in the spanner maker's embossed lettering.

Professor Leighton tried to sell the idea of using StarStream to fight AMR by cleaning medical and dental instruments to medics. They kept coming back with the question: does it clean or does it kill? This response turned Professor Leighton into an evangelist for alternatives to antibiotics for tackling AMR. "Cold water cleaning that cleans without killing seemed to me to be a godsend. It protects the skin and doesn't promote resistance; and yet no-one I spoke to could see the reason for it." They all wanted to emulate antibiotics and to kill the bacteria. "That was one reason why I really brought an engineering approach to AMR. The saviour for humans in terms of AMR isn't new antibiotics – they will only give us 10 more years – it is your skin." Deny bugs entry to the body, by cleaning, looking after the skin and protecting breaks in it, and you vastly reduce the risk of infection, he says.

Tackling AMR means preventing microbes from evolving resistance. "The microbes we wash away with StarStream are alive and can pass on their genetic susceptibility to washing to the population in the wider world, where they have lived naturally in their billions for millions of years. Do not routinely kill microbes if you want to defeat AMR. If you do not change the gene pool, genetic natural selection is massively weakened." You are left with a global population of bacteria that remains susceptible to StarStream washing the next time they attach to you. Professor Leighton sees this as "a really important point in a world where everyone is so focused on finding the next way of killing microbes".

It was while trying to sell the idea that "cleaning without killing is a good thing" that Professor Leighton founded NAMRIP (Network for Anti-Microbial Resistance and Infection Prevention). Ultrasonic cleaning is certainly a part of NAMRIP, but Professor Leighton is quick to point out that it takes in much more. His engineering approach means that NAMRIP has looked at the bigger picture, starting with the problem, and has investigated many ways of tackling AMR. NAMRIP has even taken on the role of teacher, developing ways to persuade children to join the fight against AMR. His next challenge is to keep NAMRIP alive at the end of its original funding from the Engineering and Physical Sciences Research Council.

Professor Leighton's motivation is to see that the research into AMR delivers real benefits. "AMR may kill people under a massive mountain of published papers that nobody ever reads," he adds. "I am really pleased and proud of the number of people in NAMRIP who have said 'I see how we can translate research' and have started thinking about doing it and doing it properly."

NAMRIP has added to Professor Leighton's thinking on the opportunities for ultrasonic cleaning in the fight against AMR. He is not ready to say too much about all the possibilities, but he likes the idea of taking the technology behind StarStream and turning it into a way of cleaning wounds, removing bacteria so that there is no need to treat some patients with antibiotics. As he points out: "each year, 6,000 amputations in diabetics alone occur in the UK at a cost of £1 billion, because we cannot clean and heal these infected wounds."

Professor Leighton has another related idea up his sleeve. "We know that the device cleans wounds so I thought, let's try and trigger those wounds to heal as well." Early results from his team of engineers and microbiologists, working with experts in skin research in the university's Faculty of Health Sciences, show that the 'toy factory's' latest invention, dubbed StarHealer, can increase healing by around 100%.

This is just one of several ideas that Professor Leighton is reluctant to talk about too much before he has filed patents. "StarStream has got its patents all tied up. The others are on their way." Another invention sets out to clean larger surfaces with ultrasound. "Often, you want to clean a larger flat area, it could be a floor, a solar panel or anything else," says Professor Leighton. "StarGlider does this by hovering over a surface without touching it." No need for brushes or other devices that could spread contamination. The University of Southampton team has even used the StarGlider technology to clean away 'leaves on the line', the slime that is created when train wheels crush autumn leaves on rails, making them slippery and forcing trains to slow down to maintain their braking.

FROM RESEARCH TO INDUSTRY IMPACT

Professor Leighton's reticence about his new inventions is in part because he plans to accelerate the pace at which he gets the results of his research out into the world. The work behind the StarStream may have won him and Dr Peter Birkin the 2011 Royal Society Brian Mercer Award for Innovation, but it is not always easy to win research grants for this sort of work. He now hopes to take a more business-like approach to unleashing those 'toys' on the world.

The Mercer award, worth £250,000, supported the Southampton team in developing new products based on ultrasonic cleaning. Professor Leighton's current challenge is to generate enough income to bring his portfolio of ideas to market, and to support the group's basic research. As it is, industry already provides most of the money for Professor Leighton's team, but it comes in small chunks, which makes it hard to manage. He hopes to change that by bringing a steady stream of inventions to the market.

Professor Leighton understands the need to maximise the impact of the research. He managed the engineering faculty's input to the latest Research Excellence Framework (REF), which meant, as he puts it, persuading the faculty's 200 academics with cake to get them to write submissions, including evidence of the impact of their research. Perhaps surprisingly, he claims that he enjoyed the REF process. "I did love a huge amount of what REF did for impact. It raised the bar for people who were saying 'this research could be of some use to somebody, someday' to having to say 'number of lives saved, number of new doctors trained, number of new jobs, number of new dollars'."

For all his enthusiasm for REF, Professor Leighton admits that it took up eight years of his life: four spent running REF and another four rebuilding the research group that had all but disappeared during the REF process. Now back up to strength, with five PhD students and three postdoctoral researchers, all of them at least part funded by industry, the team keeps the 'toy factory' busy. This year, they will also have to find room for half a dozen undergraduate research projects working on various inventions.

What drives Professor Leighton to go beyond adding to his group's number of published papers? "I think we have got a massive responsibility. We have been given this brilliant education, fantastic research facilities, and the taxpayer pays a lot for the pleasure of us being here. Let's put something back. Let's save lives with it."

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, **1963**. Studied natural sciences, physics and theoretical physics at the University of Cambridge, **1982–1985**. Awarded a PhD for image intensifier studies of sonoluminescence with applications to the safe use of medical ultrasound, **1988**. Joined the University of Southampton as a lecturer in underwater acoustics, **1992**. Appointed Professor of Ultrasonics and Underwater Acoustics, **1999**. Awarded the Brian Mercer Award for Innovation, **2011**. Fellow of the Royal Academy of Engineering, **2012**. Fellow of the Royal Society, **2014**. Founding Chair, Network for Anti-Microbial Resistance and Infection Prevention, **2015–present**. Founding Chair, Health Effects of Ultrasound in Air, **2015–present**. Awarded the Clifford Paterson Medal by the Royal Society, **2017**.

INNOVATION WATCH

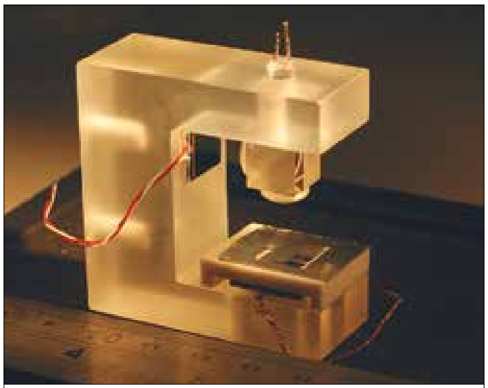
THE WORLD'S SMALLEST GRAVIMETER

Researchers at the University of Glasgow have adapted smartphone accelerometer technology to make the first small and affordable gravimeter, the Wee-g.

The Wee-g is based on technology that is used in mobile phones to measure acceleration. These devices are tiny mechanical structures made from silicon, and are called micro-electromechanical systems (or MEMS). MEMS accelerometers in phones are mainly used to measure which direction the phone is pointing in to rotate the screen when it is tilted and for apps such as compasses or stargazing. By using this technology in the Wee-g, Professor Giles Hammond and his team hope to make a gravity sensor that is significantly smaller and cheaper than those currently available.

Gravimeters are used to measure the Earth's gravitational field. Existing models are large and expensive, which can often make them impractical. They are mainly used in the oil and gas industry to discover fossil fuel deposits and are usually based around a weight on a spring that is sensitive to tiny fractional changes within Earth's gravity.

The new instrument is significantly smaller and centres around a weight hanging from microscopic springs. It is much more sensitive than the accelerometer found in a smartphone. The weight is made from a 0.2-millimetre-thick silicon wafer, with small silicon springs – 10 times thinner than a human hair – that hold the weight in place. When it is held vertically, gravity pulls the weight downwards. If the pull changes slightly, then the weight moves. This is measured by using a light and recording the movement of the shadow, which is detected by a photodiode, converted to current and recorded. As the springs are so thin, they are activated by tiny gravitational changes.



The micro-electromechanical sensor is made from silicon, and is used in the Wee-g to detect tiny changes in gravity

The Wee-g was initially tested by the University of Glasgow team by measuring the Earth's tides over several days. Earth tides are similar to the tides that affect the sea, but they affect the Earth's diameter. This means that Glasgow moves up and down by around 20 centimetres over 12 to 13 hours, resulting in gravitational acceleration that the team was able to measure. The change in gravity moves the tiny weight on the Wee-g's springs.

As the Wee-g can detect very small gravity changes, it has several potential commercial uses. The device could be used for the environmental monitoring of volcanoes and magma build-up, providing an early warning system. It could also have uses in security and defence, for example in cargo scanning. The Wee-g could be used to conduct gravity surveys, detecting underground tunnels or sinkholes before land is purchased. Civil engineers could use it to detect such features as abandoned mineshafts, and the team believes that, in the future, gravity surveys could become as relevant as environmental surveys.

The researchers recently carried out tests of the device in the field, to confirm whether it worked as expected. This was done by measuring the change in gravity when moving the device to a different altitude (this works as moving higher increases the distance from the centre of the planet). The tests were carried out in two ways: firstly, by using a regular lift, and secondly by going up and down the Campsie Fells, a range of hills in Glasgow. The researchers saw a clear change in gravity between the top and bottom points in both settings, demonstrating that, as well being able to detect small changes in gravity, the device is useful and portable outside the lab.

The Wee-g is about the size of a shoebox, and the sensor itself is the size of a postage stamp. The researchers are about to start work with Kelvin Nanotechnology to make the device even smaller. They expect that the device will be about the size of a USB drive, controlled with an electronics board that could be around the size of a smartphone.

For further information, visit **quantic.ac.uk**

HOW DOES THAT WORK?

DRONES

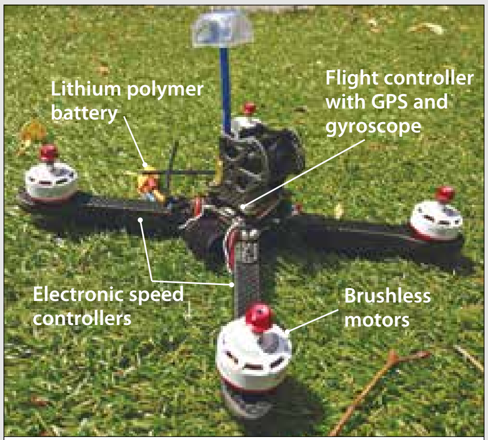
Unmanned aerial vehicles have been in operation for many years, particularly for military purposes. However, recent advances in technology have increased the potential uses of drones, such as for aerial photography, agriculture, and search and rescue.

Improvements in battery life, motor power and gyroscopes mean that users have more control over drones than ever before, while improvements in manufacturing mean that the component parts are more affordable.

Previously, radio-controlled vehicles relied on nickel-based batteries – either nickel-metal hydride or nickel-cadmium batteries – which have significantly smaller capacity per kilogram of battery than the newer lithium polymer batteries. These nickel batteries were not powerful enough to be used in drones, as in drones the thrust from the motors alone provides lift.

Most drones currently use lithium-polymer batteries, but there has been little improvement in their performance, and they are the most limiting factor for drones today. For professional drone racing, users require batteries with internal resistance values less than one milli-ohm per cell. New lithium-sulphur batteries have two to three times the capacity of the previously used nickel-based batteries, and may be the answer to the limitations of the lithium-polymer batteries. The batteries still need further work to stabilise the electrodes to prevent them from breaking down after charging-discharging cycles.

The motor technology that powers drones has also seen huge technological advances. The model aircraft of the early 2000s relied on brushed motors, a type of motor that uses brushes running inside the motor to commutate the current passing through the coils. It is mechanically complicated, but electrically simple as applying voltage across the motor makes it spin. A few years later, model aircraft enthusiasts experimented with brushless motors from CD drives. In a brushless motor, the commutation is performed electronically, using transistors to energise coils in the motor, which is more efficient than a brushed motor, and has a higher power to weight ratio. These powerful motors have more torque, or rotational force, than a brushed motor, so can produce the thrust necessary to allow drones to take flight.



The component parts of a drone

As drones are inherently unstable, the flight controller needs to adjust the speed of the motors up to 8,000 times per second. This increased torque means that the motor can adjust its speed faster than a brushed motor can, ensuring that the drone is stable. Brushless motors require an electronic speed controller to adjust the speed of the motors, which adds additional cost. However, in recent years, the price of field effect transistors, the key component of the electronic speed controller, have dropped.

Drones need constant correction to stay level. A racing drone may only require a gyroscope to stay level, but drones that are used in aerial photography require a vast array of sensors. These often include a gyroscope, accelerometer, barometer, magnetometer and a GPS receiver. The cost and size of these chips has significantly decreased over the last 10 years. For example, a suitable chip containing a three-axis gyroscope and accelerometer costs less than £2.50 today, and is smaller than three millimetres squared, 10 times smaller than a similar chip would have been 10 years ago.

Advances in GPS technology have made hobby drones successful. Civilian GPS devices included a feature known as Selective Availability, which was an intentional reduction of public GPS signals for security reasons that caused an error in the reported position of the GPS device of around 100 metres, far too much for any drone to be able to remain steady. In the late 2000s, newer modules were released that update five times a second, providing the necessary precision for drones to remain stationary to within half a metre. More recently, global positioning units have been released that can receive GPS – GLONASS (the Russian equivalent), Galileo (European) and BeiDou (Chinese) – which can relay their position up to 10 times per second with even greater precision.

BIOGRAPHY

Ossian Keith is a mechanical engineering student at Imperial College London. He runs a website based on drones, droneinsider.org, and is particularly interested in drone racing.