ingenia

MARCH 2018 ISSUE 74

PUBLIC ENGAGEMENT WITH ENGINEERING

MARY ROSE CONSERVATION

TWISTED TOWER DESIGN

MEASUREMENTS FOR MANUFACTURING

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

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
The Trent XWB engine. Image courtesy of Rolls-Royce

ISSN 1472-9768

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

Raising and conserving the *Mary Rose* p12

Measure to make better p20

A tower with a twist p26

How I got here p8

Ingenious p31

A formula for success p37

CONTENTS

UP FRONT

FEATURES

PROFILE

@RAEngNews #IngeniaMag

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

EDITORIAL

THIS IS ENGINEERING!

Dr Scott Steedman

You may not have noticed it yet, but teenagers all over the country hopefully have. Timed to coincide with the government's Year of Engineering celebration (How engineering can take its place in the spotlight, *Ingenia* 73), the Royal Academy of Engineering has launched This is Engineering (TIE). This digital communications campaign sets out to rebrand engineering for the young and explain to them what engineers really do.

Engineers constantly talk about the need to reach out to young people in a style that they will find appealing, but now it is actually happening. TIE is a sustained, national campaign aimed at 13 to 18 year olds, using social media to challenge young people to think about what engineering really means. As the Academy puts it, TIE wants to be brave and bold, "a digital campaign for a digital generation with a digital future".

Heard it all before? This time it will not be the traditional 'careers talk', but an immersive experience that highlights what engineers achieve for society and how it is relevant to young people. TIE speaks to teenagers through channels that they themselves depend on. The Academy has invited industry and the wider profession to provide longlasting commitments and to build an enduring legacy for the campaign long after the Year of Engineering.

Could this succeed? After decades of trying to move the needle through science fairs and afterschool talks, TIE deserves to be a breakthrough. Robotics and automation, machine learning and artificial intelligence, 3D printing, mobile phones, medical imaging systems, advances in sports technology, gaming and driverless cars are all in the frame.

TIE uses bold advertising online and through social media to challenge cultural perceptions by presenting a new face of engineering. The message is that a career in engineering is exciting and varied, not to mention well rewarded.

The TIE website (www.thisisengineering.org.uk) showcases young engineers' experiences of their careers in sectors as diverse as fashion and space. It already has a collection of inspiring and exciting short films of young people describing their passion for engineering in a very different format to the conventional interview. They are all compelling: in the first three weeks of the campaign, the TIE videos received over 3.5 million views. To take just two, you should watch Pavlina the 'light painter' working in the fashion industry and Chris, the medical robotics 'body rebuilder'.

TIE also links teenagers to the EngineeringUK programme Tomorrow's Engineers (www.tomorrowsengineers.org.uk) for practical advice on how to get into engineering. This programme is designed for a school-age audience and tackles the challenge of delivering relevant, attractive careers information head-on by providing teenagers, parents and teachers (who also need to understand what engineering is really about) with the information they need in an appealing and relevant format. Under the Tomorrow's Engineers banner, EngineeringUK supports employer engagement activity with schools, providing materials and engagement opportunities to schools across the country. TIE and Tomorrow's Engineers are working together to develop school resources based on the TIE messaging.

With all this activity, the challenge will be to keep the content and messages dynamic, topical and enduring. Industry and technology companies are being encouraged by the Academy to step up their support and become partners for TIE, but to make a real difference, the whole profession needs to promote this initiative at every opportunity and at all levels, local and national.

The scale of the challenge bears repeating. EngineeringUK estimates that every year the UK experiences a shortfall of 20,000 new engineers and technicians. Filling this gap means significantly increasing the number of students and apprentices entering the industry. Input to the government in April 2017 from the 38 professional engineering institutions coordinated by the Academy *(Engineering an economy that works for all)* highlighted skills as a major risk to future economic growth. The government's industrial strategy White Paper, published in December, acknowledged the scale of the crisis.

So let there be no more handwringing. It is time for action, not words. If you're a teenager, try the links! What the UK needs is a commitment by engineers and their companies, large and small, wherever they are based, to get involved with this important and exciting campaign. TIE needs your support to find and attract the next generation of engineers. This time, let's move the needle.

Dr Scott Steedman CBE FREng
Editor-in-Chief

GUEST EDITORIAL

ENGINEERING FOR SOCIETY

Dr Hayaatun Sillem

Engineering and technology are playing an ever more visible role in the world around us. So many of the topics that feature in the media, in Parliament and in everyday conversation are issues on which an engineering voice is important. From the impact of AI and automation to air quality, the challenges faced in the NHS and in housing, and the need to improve economic opportunity in underserved regions of the UK – these are issues that engineers, working with others, can help to address. I am delighted that I have been given the opportunity to lead the Royal Academy of Engineering into its next phase of development and am deeply committed to ensuring that we succeed in our mission to promote engineering excellence for the benefit of society. If we achieve this, we will be playing an essential role in national life.

Leadership is at the heart of our identity as a national academy and depends on us building strong partnerships right across the engineering community. A key priority for the year ahead is to establish a new Engineering Policy Centre, with participation from all the UK's professional engineering organisations. Our objective is to boost our collective ability to engage with policymakers on important strategic issues such as future energy supply and engineering skills. We want to enhance the visibility and influence of the engineering profession at the highest levels of both regional and national government, so that we can better support those who make decisions on behalf of the public.

Another crucial area in which we are seeking to provide leadership is diversity and inclusion. It is a source of frustration and disappointment that we still have a UK engineering workforce that is 91% male and 94% white, especially at a time when we are facing significant shortfalls in the numbers of engineers joining our profession. The Academy leads a major programme to accelerate the rate of progress towards creating a profession that can inspire, attract and retain people from all backgrounds and that better reflects the society we serve. Recently, we have increased our focus on fostering an inclusive culture within engineering – something that engineers from all backgrounds can contribute to and benefit from. Last year, we conducted a groundbreaking study on how the culture in engineering is perceived, which nearly 7,000 UK engineers participated in. We are continuing to use the evidence this uncovered to drive the development of practical tools to promote inclusion within our profession.

Engineering's role in enabling and accelerating growth, including through research and innovation, is well recognised and will become even more important as the UK leaves the EU. The Academy supports outstanding engineering researchers at all career stages, attracting the best talent to work on the problems and opportunities that matter to industry. I am delighted that recent funding boosts from the government's Investment in Research Talent are enabling us to support more excellent researchers than ever. It is also helping to ensure that emerging technologies with the potential to deliver significant economic and social impact continue to be advanced within the UK.

We are also working with engineers around the world to enhance the ability of our talented researchers to make people's lives better. For example, the Frontiers of Engineering for Development programme brings together UK and international early-career researchers from across and beyond engineering to explore what they can achieve through collaboration. For attendees, this can be a transformational experience that opens their eyes to the breadth of impact that engineering – and their research – can help deliver. Engineering is a vital contributor to global development: engineers, working in multidisciplinary teams, will play essential roles in addressing the UN's Sustainable Development Goals.

Another major focus of our international programmes is innovation and enterprise. So far we have trained over 600 budding engineering entrepreneurs from 16 emerging economies under our Newton Fund Leaders in Innovation Fellowships. This scheme grew out of our UK-based Enterprise Hub, which celebrates its fifth anniversary this year. The Hub supports both engineers who are embarking on their entrepreneurial journey and leaders of established engineering SMEs. In addition to funding, we connect them with Academy Fellows and other experienced entrepreneurs who can support and advise them as they set out in business. We now have 73 Hub members, who have raised over £60 million in investment funding and created 57 new companies, generating 270 high-quality jobs.

This is an exciting time to be taking on the role of CEO. I look forward to working with the wider engineering community to make sure that during this Year of Engineering we showcase what modern engineering can offer, build partnerships across the profession, and kick-start efforts to attract a new generation of engineers who better reflect the society we live in.

Dr Hayaatun Sillem
Chief Executive
Royal Academy of Engineering

IN BRIEF

YEAR OF ENGINEERING AT THE LONDON TRANSPORT MUSEUM

The interactive exhibits in the London Transport Museum's new galleries aim to engage more young people with STEM subjects and demonstrate how engineers have contributed to London's transport system over the past 150 years
© London Transport Museum

To celebrate the Year of Engineering in 2018, London Transport Museum is launching two new permanent galleries alongside a programme of events and activities throughout the year.

On 23 March, the *Digging Deeper* gallery will launch. It will explore the history of tunnelling, including the Thames Tunnel, the London Underground and Crossrail, and display models, drawings and artefacts from 1840 to the present day.

The gallery will feature a life-size recreation of the tunnelling shield that dug the world's first electric tube line in 1890, contrasting it with digging machines used to construct the new Elizabeth line (Crossrail).

On 13 July, the *Future Engineers* interactive gallery will open with the aim of engaging young people, parents and schools with science, technology, engineering and maths (STEM) subjects and challenging their perceptions of engineering. It will showcase the role of modern engineering: highlighting examples of cutting-edge engineering and technological innovations through hands-on exhibits, including a state-of-the-art train-driving simulator. The gallery draws on the Royal Academy of Engineering's *Thinking like an engineer* report. It will invite 'future engineers' to ask themselves if they are dreamers, planners or fixers, and explore the 'engineering habits of mind', identified by the report, through case studies and activities that allow visitors to try to solve engineering challenges.

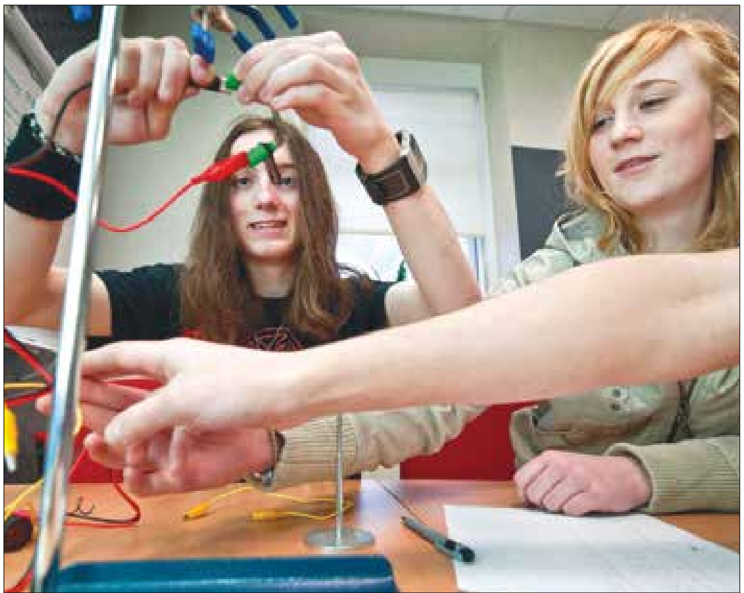
The museum is also hosting a temporary exhibition on Crossrail, Europe's biggest engineering project, which opens on 23 March.

It will hold a series of family activities and workshops, where visitors can meet real engineers. An open weekend at its Museum Depot in Acton will explore how engineers have kept London moving for the last 150 years.

London Transport Museum is a partner in the Year of Engineering and is working with Transport for London and the Department for Transport to engage more young people in engineering.

For more information about the galleries and events, visit **www.ltmuseum.co.uk**

UTCS CREATE WORK-READY STUDENTS



Employers involved in UTC education described their students as "young professionals ready for work"

The first evaluation of University Technical College (UTC) approaches to curriculum design and employer engagement has found that project-based learning and employer involvement have helped create more well-rounded, work-ready students. The National Foundation for Educational Research carried out the report on behalf of the Royal Academy of Engineering and the Edge Foundation to evaluate the UTC model to inform sector-wide practice.

It found that students at UTCs develop more work-ready skills such as project management and good communication alongside their technical skills, and that students felt more confident about their next steps after UTC education.

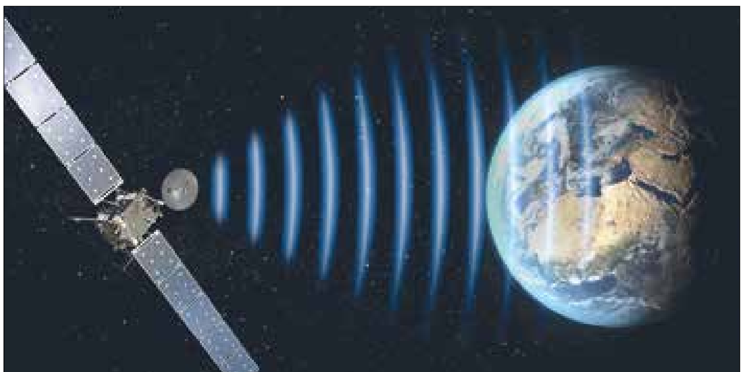
The study team visited 10 UTCs, which all showed evidence of considerable employer awareness and presence. This included: informing the curriculum with current industry skills needs; observation and experience of everyday industry activity; genuine, authentic challenges or problems for young people to solve; ongoing, regular input into projects; provision of visits to employers' workplaces; employer talks; resources and facilities; and specialist sector expertise.

However, the UTCs acknowledged that they face challenges in recruiting suitable employers and enough numbers of students, as well as in recruiting and keeping high-calibre staff. Despite this, they reported that many students make significant progress – often performing better than expected on arrival.

Dr Rhys Morgan, Director of Engineering and Education at the Royal Academy of Engineering, said: "Every effort should be made to address the engineering skills gap in this country and UTCs are an important avenue into technical careers. There are clear benefits of employer involvement in UTCs for both industry and students alike. All UTCs in this report had an employer presence, but the varying approaches to employer involvement and the challenges of finding the right employers to involve need to be addressed as this type of technical education evolves and matures."

To read the report in full, please visit **www.raeng.org.uk/publications/reports/evaluation-of-university-technical-colleges**

EXPLORE SPACE AT *INGENIA LIVE!*



***Ingenia live!* will feature talks from engineering innovators in the space industry** © ESA-C.Carreau

In April, the latest *Ingenia live!* event will look at the innovative engineering technologies that are helping to advance space exploration.

Taking place at Prince Philip House in central London, the event will host talks from leading engineers in the space industry, including Shefali Sharma from Oxford Space Systems.

The event will be chaired by Dr Scott Steedman CBE FREng, Editor-in-chief of *Ingenia*, and will be followed by a Q&A session and a networking reception, which includes food and drink.

Ingenia live! brings to life the stories featured within the magazine, covering a range of engineering disciplines.

Tickets cost £10 and students can attend free of charge. To find out more about the programme and register to attend, please visit **www.raeng.org.uk/events**

DIGITAL CAMPAIGN AIMS TO TACKLE SKILLS SHORTAGE

Vinita, who works at the European Space Agency, is one of the engineers featured in the This is Engineering campaign

In January, the Royal Academy of Engineering launched the This is Engineering campaign in collaboration with EngineeringUK and a host of industry partners. It aims to give more young people from all backgrounds the opportunity to explore how they could pursue what they love and follow it into a career in engineering in a range of industries, such as film, sports, gaming and music.

This is Engineering aims to reshape young people's perceptions of careers in engineering, which they often view as narrow, technical and traditional. The campaign launched with online advertising focusing on five young engineers who have turned their passions for sport, design, fashion, technology and space into engineering careers, demonstrating that the profession is diverse, challenging and creative.

Several major engineering companies are backing the campaign, which coincides with the government-led Year of Engineering, in response to significant demand for engineering talent in the UK. Findings from a forthcoming EngineeringUK report identify a need for at least 124,000 engineers and technicians every year.

Nusrat Ghani MP, Minister for the Year of Engineering, said: "Careers in the industry are a chance for young people to shape the future and have a real impact on the lives of those around them. Role models are a vital way of showing this, and it's fantastic to see This is Engineering celebrating exciting and unexpected stories of modern engineers."

Mark Titterington, CEO of EngineeringUK, said: "The demand for people with engineering skills continues to outstrip supply … there's more to be done. I continue to be amazed by the diversity of the opportunities that engineering can provide and the challenges that engineers can overcome. It's vital that young people are able to see and be inspired by the diversity and the creativity of the profession. That's where This is Engineering comes in."

Visit **www.thisisengineering.org.uk** to watch the films of the engineers and find out more about a career in engineering, and follow **@ThisIsEng** on Twitter.

HOW I GOT HERE

Q&A

ELLIOTT WEBB
APPRENTICE ENGINEER, ARUP

Through his apprenticeship at Arup, Elliot Webb is gaining practical engineering experience

Elliott Webb is an apprentice engineer in Arup's Highways team. He is currently designing and modelling routes for the High Speed 2 (HS2) project.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

When I was 11, I went on a family trip to France where we crossed the Pont de Normandie, a cable-stayed road bridge across the Seine. I was amazed by the engineering involved in such an impressive bridge and it sparked an interest about how things are made, designed and how they come to life. I've always liked the idea of being able to design something and then see it built; the thought of designing something in an office and then taking my family and friends to see it in real life was what first inspired me to become an engineer. I can't wait to say to my family: "Look at what I've designed!".

HOW DID YOU GET TO WHERE YOU ARE NOW?

I knew I wanted to be an engineer from an early age, so I looked into what subjects I would need to do that. Maths and sciences seemed essential, and I've always been quite good at maths so that was an obvious choice. I ended up studying maths, physics, and business at A level. Business might seem like an odd selection, but it helped me to understand how companies are run and how an engineer's everyday decisions can affect a company.

The thing that helped me most was doing a work placement at an engineering company. It was a small company, so I got a great understanding of how it worked from shop-floor to director level. I could take a step back and see how the whole company operated, and it gave me a good insight into what it's like to be an engineer. I could speak to different engineers about what their day-to-day life was like, so learned about the different career directions I could choose. It also helped me in my interview with Arup, as I could bring along drawings that I'd done on an old-fashioned drawing board during the placement to demonstrate my work.

I chose to do an apprenticeship after speaking to engineers during my work placement. Many said that to be a truly good engineer, it's important to have experience from the bottom upwards, which sometimes you don't gain as an undergraduate. The apprenticeship will give me a qualification through college and university, and it's all paid for. I can gain the knowledge that engineers need but can also learn technical skills, which I think is really vital. I will also be able to do a degree through Arup, but I wanted to have the practical experience first. I knew that I could go to university at any time, but I wanted to start work and know that I had a genuine passion for the job before committing to a degree.

HOW DOES THE APPRENTICESHIP WORK?

The Arup apprenticeship works in two-year blocks. For the first two years, I've been working on gaining my BTEC Level 3 in engineering, and in September I'll start my second two-year block, which will be working towards a Higher National Certificate in civil engineering. I spend one day a week going to college, and it can be quite challenging to balance the four days a week of office work with the one day of college plus assignments, presentations and reports. Arup has also recently added the option of staying on a further three years to incorporate a degree. I would like to do the full seven years – it sounds like a long time but it will take me from having zero experience to having a degree and seven years of experience working on projects. My degree will be civil engineering, but what you specialise in is based on your team, so mine will probably be highways related.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

I think my biggest achievement has been getting the apprenticeship at Arup. Apprenticeships are competitive, so to get one with a big company is an achievement in itself. The opportunities that are now available to me because of this apprenticeship are phenomenal. To be working on HS2, which is the largest infrastructure project in Europe at the moment, at the age of 19 is amazing. I didn't know what I'd be working on when I applied, so I was thrown in at the deep end on my first day. I feel really lucky to be working on such a landmark project, and to have designed things that are going to be used on HS2!

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

Every day is different – even when I'm working on a single project, I'm still never doing the same thing as tasks change as they progress. It's never mundane. I'm always excited to get to work and get started on whatever I'm working on that day. It's so important to love what you do, and I'm lucky enough to enjoy what I do every day.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

I live about 30 miles away from work, so I get up early at about 5am. When I arrive, I talk to someone in the team to discuss the day's tasks and timeframes, and think about the best way to go about my task for the day or week. Now I've been here for over a year I'm starting to get more responsibilities and gaining more trust, resulting in more varied and high-level work.

A typical task might be looking at re-routing the construction traffic from one road to another route. I would need to assess the existing roads and see if they allow for the proposed construction traffic. Having identified areas that are not to standard, I would then need to model the roads to make sure that they are suitable by completing a 2D horizontal and vertical alignment for the new road. Then I would use computer-aided design programmes to model it further in 3D, creating a corridor model, which is essentially the finished product that shows all the information about the road such as the carriageway, verge, earthworks and centreline.

A computer-generated image of the HS2 project © Arup

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

The best thing to do is to get a work placement, so that you can discover what type of engineering interests you. There are different routes into engineering, through degrees or apprenticeship, but there are also so many different types and disciplines within engineering. You can be site based or work for a contractor or a consultant; you could work in civil, chemical, environmental or nuclear engineering. It's great to get experience so that you can narrow down the options. I got the work experience through school, but if your school doesn't offer it, it's worth trying to find a way of getting experience. A lot of bigger companies offer summer placements, which look great on applications for apprenticeships or universities, as work experience shows initiative and enthusiasm.

WHAT'S NEXT FOR YOU?

My next aim is to get some different experiences within Arup, for example getting out on site a bit more, or doing a rotation into a different discipline such as bridges to see how it interacts with highways. I'm also going to take part in the 2018 MERIT competition run by the Institution of Civil Engineers, which is an international construction business game that involves teams competitively running a construction company through a computer-based simulation. MERIT stands for management, enterprise, risk, innovation and teamwork, and the competition aims to enable young engineers to acquire these skills. I'm working with a team on that at the moment.

QUICK-FIRE FACTS

Age: **19**

Qualifications: **A levels in maths, physics and business**

Biggest inspiration: **Isambard Kingdom Brunel**

Most-used technology: **my computer**

Three words that describe you: **driven, reliable and approachable**

OPINION

COLLABORATION IS KEY TO IMPROVING THE UK'S PRODUCTIVITY

Britain's construction sector is experiencing its lowest levels of productivity in more than 40 years. According to Sir John Armitt CBE FREng, Chair of the National Infrastructure Commission, this is the result of several different factors. He believes that better collaboration between clients, suppliers and construction professionals could lead the way in improving UK productivity.

Sir John Armitt CBE FREng

A colleague recently commented that Britain's construction contractors had achieved a world first in building projects successfully and losing money at the same time. I responded that this was a reflection of the industry's failure to integrate design and construction into contractual conditions. The poor productivity record of the industry flows from the same underlying problems, together with other factors. However, what is interesting, as revealed by the excellent *Reinventing construction: a route to higher productivity* report by McKinsey in February 2017, is that Britain is not alone in having this productivity problem. In particular, the US, often held up by some as being much ahead of the UK in productivity, has seen a fall in construction productivity to levels below those of 1968. The report's conclusions as to why the sector has poor productivity carry no surprises and have been evident in other studies, which compare UK project costs with mainland Europe.

So, what are the characteristics of the UK construction sector that result in poor productivity and what needs to be done to improve it? I would suggest the following. To begin with, the largest contractors lack financial scale and a global presence. They are undercapitalised but take significant price and programme risk. This is laid off through multiple subcontractors who themselves lack scale. The Carillion debacle is, in my view, an extreme example of these factors combined with poor governance.

This is not a product sector with multiple sales such as cars or mobile phones. Virtually every project is a one-off, albeit there can be repetition in types of building process. Too often, the design and build processes are separate. How can there be any rationale for separation? In any other sector, design and assembly go hand in hand. In construction, design sits in too many hands.

A further obstacle to productivity is the lack of investment in the industry. Very low margins leave little or no money to invest in R&D on materials and techniques. New ideas are most likely to come from the supply chain, such as temporary works systems, but they cannot be used to their full effectiveness if these are not part of overall design considerations.

Lack of training is a further challenge for construction. The industry's culture is one of 'get the work and then worry about resources'. It copes, so there is no real incentive to train. In a strong market in the late 1980s, at Laing we successfully recruited site engineers for Sizewell B Nuclear Power Station from all over the world to fill our needs. Since those days, expansion of the EU has provided a steady influx of skilled, hardworking individuals, reducing companies' need to invest in vocational training. Parents and teachers are still unlikely to encourage children into engineering and construction, wrongly perceiving it as dirty, poorly paid and dangerous.

Quality of leadership is at the heart of any industry and its performance. After 30 years as a contractor and 20 as a client, I am in no doubt as to who is ultimately responsible for the performance of our industry: it is the buyer, the client. Change comes through leadership. The client is best placed to determine contract form, quality, sustainability, training levels, in fact all the key values of the industry. Few do it on a consistent basis, but the Infrastructure Client Group, which was formed by the Institution of Civil Engineers just over two years ago to improve the efficiency of the construction sector, does recognise the issues. Its Project 13 initiative, which aims to build better relationships in the construction industry to improve productivity and performance, promotes best practice but will require widespread take-up and strong leadership to be effective.

So, what is needed to overturn these weaknesses? To my mind it must start with client leadership. The way that the industry delivers is determined by the client. An intelligent client who commissions projects on a regular basis is in the best position to understand the required outcomes and what works.

Water utility clients have adopted the five-year framework or alliance approach. They select designers and contractors as their suppliers and partners without a full knowledge of the scope of projects over the period. The criteria will be a balanced scorecard, including factors such as ability of designers and contractors to work together, risk sharing, safety, experience of staff, costs, innovation, community relations, environmental policies and a training agenda. The client will look for an alignment of values and willingness to seek ways to reduce unit costs

If the whole construction industry used this approach, the opportunity for productivity improvements would be enormous. In addition, the opportunities created by the full application of BIM (building information modelling) and remote condition monitoring, which uses a strategic approach to technology, information management and business process to deliver benefits in performance and long-term asset management, would provide further benefits through data. This can support future design optimisation and asset management.

Do clients outside of utilities and major projects such as Crossrail have the scale of investment to warrant the water companies' approach? I would argue many do: major house builders, major retailers and commercial developers could all take a more collaborative approach with their supply chain. However, it will require a move away from the traditional approach of first commission the architects, then the engineers, then appoint the contractor with the lowest price on tough contract terms.

An industry based on collaboration with more continuity of relationships, sensible pricing and allocation of risk is one more able and likely to take hiring and training seriously and invest in developing new processes, including off-site manufacture.

The big, vertically integrated European contractors with large balance sheets who also own infrastructure will continue to thrive. Only with the sort of major change I have outlined and a stronger capital base will there be the opportunity for a few UK companies to maintain a prime contractor role.

Government absolutely has a role in improving productivity: first, by adopting the recommendations of the National Infrastructure Commission to provide a long-term plan and greater continuity in the workload for industry; and secondly, as a client, with strong leadership from the Infrastructure Projects Authority, supporting initiatives such as Project 13. It also has a role through education policy, with more emphasis on STEM, especially among 5 to 12 year olds, so that there is a solid grounding, confidence and enjoyment of these subjects before they move into secondary education where its importance must be sustained.

Britain has many of the most respected construction professionals in the world, especially in architecture and engineering. The UK's contractors may have withdrawn from some overseas markets, but they are still recognised for their skills in project management. If clients lead and encourage more collaboration between themselves and the sector's professions, we could see productivity improvements of up to 50% among contractors and suppliers. This is vital if we are to deliver the infrastructure the country needs, but which, without improvements in productivity, we cannot afford.

BIOGRAPHY

Sir John Armitt CBE FREng is Chair of the National Infrastructure Commission, the National Express Group, the City & Guilds Group and Deputy Chairman of the Berkeley Group. He is a past President of the Institution of Civil Engineers. Previously, Sir John was Chairman of the Olympic Delivery Authority, a member of the Airports Commission, Chief Executive of Network Rail, Costain and Union Railways. The first 27 years of Sir John's career were spent with John Laing Group.

The Mary Rose Museum is alongside HMS *Victory* in Portsmouth's Historic Dockyard, close to where the Tudor warship was originally constructed in the early 1500s, and subsequently sank in 1545. © Hufton+Crow

RAISING AND CONSERVING THE *MARY ROSE*

The Mary Rose Museum has been shortlisted for the 2018 European Museum of the Year award. It houses the Mary Rose hull and thousands of Tudor artefacts that were sealed under clay and silt when it sank in 1545. Technology has helped detect, rescue, resurrect and conserve the remains of Henry VIII's warship since the mission to find it began in the 1960s. Engineering writer Dominic Joyeux talked to Dr Eleanor Schofield, Head of Conservation and Collections Care, and Christopher Dobbs, Head of Interpretation and Maritime Archaeology, to find out more.

On 19 July 1545, an army sent by Francis I, King of France, tried to enter Portsmouth Harbour to land troops and go into battle with the English. As skirmishes began, a strong wind picked up enabling the 34-year-old English warship *Mary Rose* to gather speed and confront the French galleys.

What happened next, and why, has been the subject of much conjecture; a mix of poor communication, strong winds and overloading did not help the *Mary Rose*. What is certain is that the 600 tonne warship suddenly heeled over to its starboard side where water rushed into its open gunports and it quickly sank.

The warship sank 15 metres and lodged itself at a 60-degree angle to starboard on the soft clay of the seabed. The first attempt to salvage it was attempted a few days later, but the tried method of lifting wrecks from shallow waters did not work as the cables could not be passed under the hull and only some rigging and guns were brought to the surface. Apart from cursory excavations by pioneer divers in the 1830s, the hull laid untouched for over 400 years.

ARCHAEOLOGICAL EXCAVATION

The destructive activity of fungi, bacteria and wood-boring crustacians and molluscs began to break down the ship's structure. After exposed parts of the ship had collapsed, the site was naturally covered by silts and eventually became the same level as the seabed. A hard, shelly layer of sediment sealed the site and helped to prevent microorganisms from further damaging the ship's wooden frame and locked in its remaining contents, as well as hiding the vessel from sight.

The search for, and discovery of, the *Mary Rose* was driven by a local historian and writer Alexander McKee, who later became Director of Excavations. From 1965 onwards, in conjunction with the local branches of the British Sub-Aqua Club, he set up 'Project Solent Ships' to look for wrecks in the Solent. For the first time in the UK, sub-bottom profiling, using sonar scans to identify and characterise layers of sediment or rock under the seafloor, was carried out by his team to look for archeological sites.

In the late 1960s, a combination of dual-channel sidescan sonar, which is a sonar device that emits conical or fan-shaped pulses toward the seafloor and records the acoustic reflections, and sub-bottom profiling revealed an anomaly in an area of the seafloor thought to be the resting place of the *Mary Rose*. The monitoring equipment sent down sound pulses to reflect or penetrate the seafloor. Those that did penetrate were either reflected or refracted as they passed through different layers of sediment and these signals were gathered by the surface vessel.

When Henry VIII's flagship the *Mary Rose* heeled over with water rushing into the lower open gunports many men were trapped by the anti-boarding netting on the upper deck, which was designed to stop raiders getting on. It is estimated that more than 400 men drowned that day
© Geoff Hunt (artist)/Mary Rose Trust

A second geophysical survey using two pingers operating at frequencies of 5 and 12 kilohertz discovered four more anomalies. This was sufficient enough to point the search team to the vessel's resting place.

A team of volunteer divers explored the area. Using water jets and airlifts, they began to excavate and were encouraged by the appearance of stray pieces of timber. The breakthrough came in May 1971 when a diver found three of the port frames of the *Mary Rose*.

The silt had preserved the buried items and divers began to bring a veritable Tudor treasure trove to the surface. Between 1979 and 1982, 28,000 dives brought up 19,000 artefacts, including cannons, gun carriages, wooden tankards and even nit combs. The objects went into 'passive' storage to stop any deterioration before conservation could begin.

The dives had revealed a significant part of the hull, which was shown to be worth saving. There was plenty of publicity around the sunken ship with the world's first live underwater broadcast taking place on the wreck site. This, and further funding raised under the patronage of HRH The Prince of Wales, meant that the project attracted enough finance and expertise to attempt to raise the hull.

BACK TO LAND

There were few precedents for raising centuries-old sunken ships onto dry land. The most relevant was the Swedish 17th century warship *Vasa*, which had been lifted to the surface of Stockholm harbour 20 years before. There is a strong link between the teams who work on the *Mary Rose* and the *Vasa*, who continue to contact each other at all levels, be it for conservation, research or even museum activities.

The *Vasa* had been lifted using cable slings passed underneath the hull, which were then attached to two pontoons above and gradually raised. The *Vasa* had rested upright on the sea bed and had most of its hull intact. However, this was not the case with the *Mary Rose* and so a new method had to be developed.

In 1979, a meeting of salvage consultants and contractors, structural engineers and naval architects agreed that it should be possible to reinforce and recover the hull. Although the remaining hull was an open shell, rather than a complete cross section with transverse strength, a plan was drawn up [*see Raising the* Mary Rose].

On 11 October 1982, media gathered from all over the world and an estimated 60 million people watched the raising of the hull on television. Above the water, a giant floating crane called *Tog Mor* took the strain and transferred the hull frame onto the cradle as divers monitored the process on the seabed. The crane winched the cradle very slowly to the surface, where the hull encountered air again for the first time in 437 years.

There was an initial scare when the filming showed one corner of the frame slipping toward the hull due to a mistakenly applied strop and some securing pins. However, shortly after, the crane placed the yellow frame on a barge and took it to Portsmouth Historic Dockyard's dry dock number three, close to where Henry VIII had the warship built nearly 500 years before.

The crane lifting the Mary Rose hull out of the Solent, lying on its yellow cradle, is an image that millions of TV viewers retain from the memorable morning of Monday 11 October 1982 © Christopher Dobbs/Mary Rose Trust

PRESERVING THE HULL

For the first few weeks of 'passive holding', a pumping system kept the timber work of the *Mary Rose* soaked, enabling thousands of litres of seawater a minute to pass over it. The ship's conservators then switched this to freshwater and a chilling system held the water at 2°C to discourage microorganisms. They then placed a temporary building around the hull, which was to stay in place for the next 30 years to enable both public viewing and a controlled environment.

Left exposed to air to dry out, the ship's wooden structure would have collapsed and shrunk as the water evaporated from its cellular structure. The

RAISING THE *MARY ROSE*

The first step of the plan to lift the *Mary Rose* tackled the problem of 'bottom suction', whereby the ship was embedded within the silt and clay of the seabed. This was achieved using 12 hydraulic jacks raising a lifting frame slowly [*Figure 1*], over a period of several days, up its four legs.

A network of bolts and internal lifting wires was created, rather than the traditional salvage method of using external strops. This spread the loading of the lift across the entire structure of the hull, avoiding the need for heavy stiffening inside the hull. Each of the 67 main lifting points had a bolt passed through the hull that, when tightened down onto the internal and external spreader plates, acted as clamps to hold the hull firmly together. The salvage diving team fitted a further 103 bolts to act as additional clamps.

Once each section of the hull was wired up to the lifting frame, the hull was undercut to find the next row of backplate positions. This meant that the divers always worked under areas of the hull that were held up from above. The divers carried out this work using a combination of a water jet to cut through the hard clay with a 150-milliimetre airlift to extract the spoil [*Figure 2*]. It was too dark and murky to see anything, so the team placed steel rods in the bolt holes that helped the divers to locate the next area by feel.

The team carried out this work during 1982, with an October deadline for the lift. At that point, the newly exposed hull would be at the mercy of winter tides and currents that would be archaeologically damaging. Nevertheless, the last two months represented diving marathons for the professional divers, staff and Royal Engineers working to the underwater salvage timetable.

Babcock Power Construction commissioned a lifting frame and a cradle to place the *Mary Rose* into. Sub-contractor Barnshaws Section Benders used section drawings made from the archaeological surveys to produce beams that formed the cradle that would hold the 35-metre-long, 14-metre-high hull of the warship. The cradle, lined with air bags, dropped down beside the hull a few days before the lifting operation began.

Once the hull was hanging freely from the lifting frame, clear of the sea bed, it was transferred underwater to the cradle [*Figure 3*]. This supported the hull, which was sitting on inflated air bags, both below and above and meant that it was ready to lift.

Christopher Dobbs, Head of Interpretation and Maritime Archeaology, and a member of the original salvage team, demonstrates how the Mary Rose *was lifted in this short film* ***www.youtube.com/watch?v=tQiYpCJB6V0***

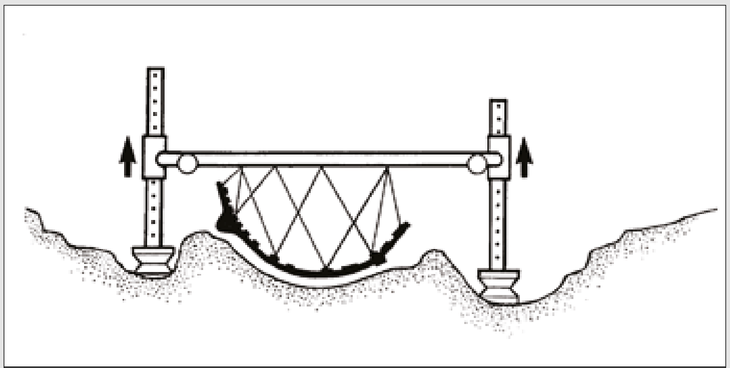


Figure 1 © Mary Rose Trust

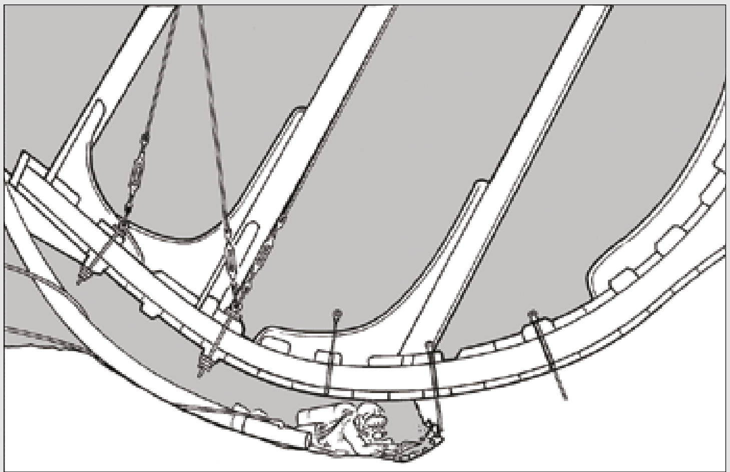


Figure 2 © Jonathan Adams/Mary Rose Trust

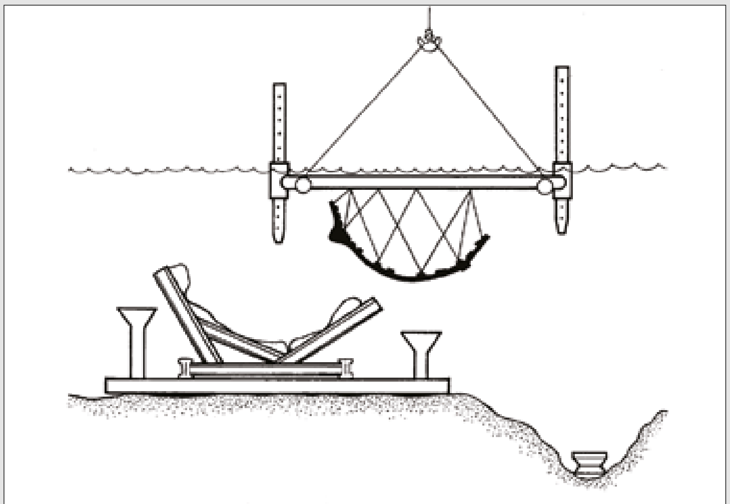


Figure 3 © Mary Rose Trust

The Mary Rose team soaks the wooden artefacts in PEG for a few years and then, because they still have water in them, freeze-dry them. At six metres long, the Mary Rose freeze dryer (right) is the largest in the country. The chamber freezes the items and any remaining water turns to ice. A vacuum then applies pressure that causes the ice to sublimate and turn straight from solid to gas. Because the water comes out very quickly, it means that the dimensional changes are minimal and the process is relatively quick. The gun carriages, for example, only took three months © Mary Rose Trust

freshwater soaking continued for a decade while the Mary Rose team worked with experts around the world to decide on the best method for conserving the hull. The team sent sample parts from the ship for testing in France by passing cold dry nitrogen over them and to Holland for controlled air-drying.

The Mary Rose team settled on using polyethylene glycol (PEG) to replace the water in the cellular structure of the wood. In the 1980s, the team that raised the Swedish warship *Vasa* sprayed this solution on the ship for 17 years, and the team that preserved the Bremen cog in Germany, a late medieval merchant ship, immersed the vessel in a giant tank of the solution for 18 years.

From 1994 to 2006, a low-grade polymer with a short chain length was used, which goes further into the wood and is liquid at room temperature. Then from 2006 to 2013, a higher-concentrate PEG, which is a solid at room temperature, was used that needed to be heated to approximately 28°C to form a solution in water. The chamber that contained the hull for all these years was dubbed 'the hot box', even more apt when, in the final few months, the temperature reached 30°C and the humidity was nearly 100%.

As well as stabilising the hull with PEG, further measures have protected the wood. One of the major enemies of sunken wrecks is the corrosive effects of iron. The *Vasa* warship has suffered greatly from this as the bolts, nails and metal fittings corrode, leaving iron deposits. It was also discovered that PEG corrodes iron and the PEG spray treatment can carry the iron deeper into the timber where it can catalyse the oxidation of sulphur, forming sulphuric acid.

The timbers on the Mary Rose hull were fortunately held together using trenails, hard wooden pegs. However, there was still some iron in the wood probably caused by nearby artefacts and seawater, and the bolts used to salvage the hull needed to be replaced. Titanium bolts replaced the steel ones before the PEG spraying and titanium was used for the modern support beams that hold up the decks to this day.

Titanium was used because it is strong, light and inert, so would not corrode. A support system was designed whereby titanium beams ran along the main and upper decks. Titanium props were fitted in between as they are adjustable and give flexibility as the ship moves over time. Before the deck timbers were put back in place, the hull had to be turned into an upright position in a major engineering operation performed in 1985. It is not perfectly upright in relation to its keel as the structure is more comfortable leaning back at an angle of three to five degrees.

BUILDING A MUSEUM

In 2013, when the correct level of PEG was reached, as determined by gel permeatation chromatography, the decision was made to turn off the sprays within the hot box and to start drying out the *Mary Rose*. A few years before, thanks to fundraising efforts and a generous allocation of Heritage Lottery funds, the Trust had started to prepare a new museum to house the hull and display its artefacts.

Since 2009, building work had been going on around the hot box and a new building had been devised from the inside out. It all developed from the hull sitting in the dry dock contained within the hot box. The hot box would switch from 28–30°C for PEG application to cooler 18–20°C for air-drying in 2013 and then the hot box would be taken down altogether a few years after the museum was opened. The logistics for maintaining the stable pegging and drying of the hull were complex [see *Controlling air flows* on page 18].

The end result was a building with a low elliptical shape that was partly designed to minimise the space around the hull and make it easier to maintain the temperature and humidity needed. The wooden-clad exterior was stained black as a nod to traditional boat sheds, and the interiors were decked out to reflect the dark conditions

Osteoarchaeology, the study of human remains, has made great advances thanks to the discovery of the warship, as has archaeogenetics, which is the study of ancient DNA – the likely birthplaces of the ship's crew was determined by what was found in the enamel of their teeth

that the crew of the *Mary Rose* had to work in.

The museum opened in 2013 and the following year was named *Building Magazine* Project of the Year. At the end of 2015, the ship was sufficiently dry to take out the drying ducts and at the same time the hot box wall around the ship was taken down, expanding the volume around the ship from 9,000 m^2 (square metres) to 12,000 m^2. Air locks were fitted between the gallery and the ship hall to help prevent too rapid changes of humidity and temperature when visitors circulate. Glazing was installed in 2016 to allow unobstructed viewing for the first time, instead of peering through narrow windows in the wall. There are now nine galleries that visitors can view situated on three floor levels. Most of the artefacts on display are arranged opposite the corresponding decks of the hull where they would have been found or used.

WHAT NEXT?

There have been plenty of firsts achieved with the raising and conserving of the *Mary Rose* and there are more advances that will be made in the coming years. Osteoarchaeology, the study of human remains, has made great advances thanks to the discovery of the warship, as has archaeogenetics, which is the study of ancient DNA – the likely birthplaces of the ship's crew was determined by what was found in the enamel of their teeth.

Among the ongoing innovative projects that Dr Eleanor Schofield, Mary Rose Trust's Head of Conservation and Collections Care, is involved with now, is one monitoring the evolution of sulphur and iron in the warship as it dries. Her team has taken core samples measuring approximately five millimetres in diameter and 200 millimetres long to the Diamond Light Source synchrotron facility at Harwell in Oxfordshire since 2012. By accelerating electrons to near light-speed, Diamond generates brilliant beams of light from infrared to X-rays, the latter of which the team has used to determine how sulphur and iron compounds evolve in the Mary Rose's wood when exposed to air, and the associated threat level of destructive acid formation. Gradually, the researchers have been able to pin down the transformation of the sulphur within the wood. This study of the hull at a cellular and molecular level has established that the current controls of the hull's immediate environment are working but has given the researchers an

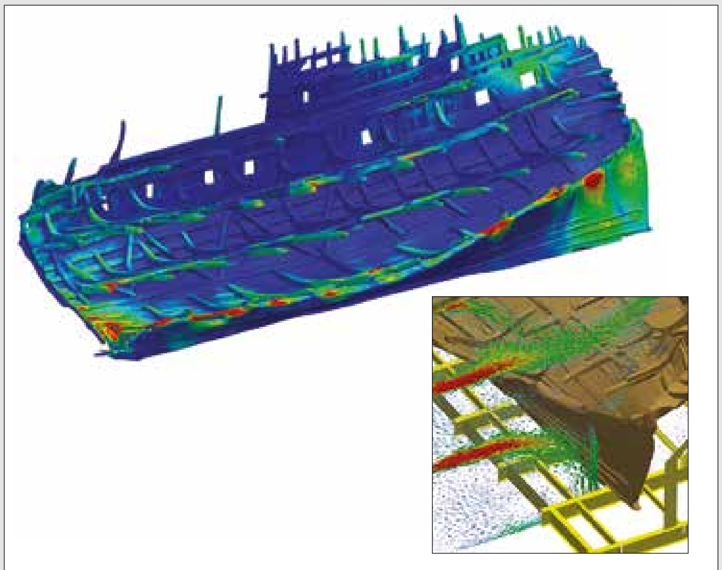
PEGGING ARCHAEOLOGICAL WOOD

There are different grades of PEG according to how many repeated units of it (CH_2-O-CH_2) make up the polymer chain. PEG works by replacing water in cell cavities and partly by bonding onto hydroxyl groups in decayed cellulose fibres. PEG embeds wood in a stable matrix.

Different concentrations of PEG were tried for differing amounts of time to see what dimensional change there was to the warship's wood. These tests were also done to see what the end result would look like, as a heavy dose leaves the wood looking black and plastic-like. The Mary Rose Trust ethos has always been to conserve rather than restore and so went for a concentration that stabilised the hull with minimal change to its appearance.

Sprays cover the Mary Rose hull with water in 1991. The hull is still on the same yellow cradle that lifted it out of the sea in 1982. It sits on the barge deck, which was cut away when it arrived at the dry dock, and rests on brick piles at a slight angle so that water and PEG solutions could drain away © Mary Rose Trust

CONTROLLING AIR FLOWS



Models of the shear stress (above) and airflow velocity (below) on the inside of the hull © K8T Limited

Consulting engineers, Ramboll UK and K8T, used computer fluid dynamics (CFD) to work out the placing of ducts and extractor fans for when the *Mary Rose* switched from PEG application to air-drying in 2013. The challenge with the drying process was to get each part of the wood to receive the same amount of air at equal velocity, relative humidity and temperature as warping and cracking would occur more rapidly if they did not. A laser scan of the ship was done, which was then used in a CFD model that took in the volume of the ship hall and then fed in the inlets and proposed pathways of the drying equipment.

Repetitions of the model were done that determined air velocities, dwell times and the shear stresses caused by air movement. Using these models, it was determined that the minimum volume of air supply needed was 25 m^3 (cubic metres) per second and three massive air-handling units (AHUs) each supplying 8.3 m^3 per second of air were placed in the dry dock with ducts feeding the air into the ship hall and around the hull.

Further stress-testing of the model identified which nooks and crannies of the ship would be missing out on air and decided the positioning of the two 1.2-metre-diameter ducts that ran the length of the hull, which in turn dropped down to supply 14 smaller ducts threaded around the beams. The designers were aiming to supply conditioned air with a maximum velocity of 0.25 m^3 per second adjacent to the hull. In order to maximise the AHU's air dehumidification, the chilled air was supplied at 2°C with the ability to rise to 6°C for the main part of the building.

To read more about the CFD modelling, see the Chartered Institution of Building Services Engineers Journal *article* Home and dry *(September 2013).*

Museum display units often have a system of humidity control within the cases. The Mary Rose Museum has a micro-air-conditioning system for its display cases, each independent of the others, which are in turn connected to the chilled water system. The museum staff set the cases to 55% humidity and 19°C, which is typical for storing organic artefacts © Mary Rose Trust

insight into how to combat deterioration in the wood should it occur.

Other projects include a research study developing 'smart' magnetic nanoparticles whose surface chemistry can be tailored with sequestering agents to remove harmful species from targeted artefacts. The Corr Group, based at the University of Glasgow's School of Chemistry, is working with Dr Schofield to help remove free iron ions in waterlogged wood, thus preventing reaction with sulphur compounds. The aim then is to find ways to sequestrate the sulphate ions.

Another ongoing project involves analysing the laser scans taken over decades at different stages of the PEG and drying process. These scans provide a unique insight into how the ship has moved, deformed, and where cracks have formed and propagated over the decades, and will help evaluate the stability of the hull and inform its future care.

It seems that even after more than 400 years on the seabed, the *Mary Rose* is the Tudor ship that just wants to keep on giving.

BIOGRAPHY

Dr Eleanor Schofield is Head of Conservation and Collections Care at the Mary Rose Trust. She completed a PhD in Materials Science at Imperial College London in 2006, then held research posts at Stanford Synchrotron Radiation Laboratory and the University of Kent. She joined the Trust in 2012 and is responsible for the conservation of the Mary Rose hull and associated artefacts, the care and management of the collection, and research into novel conservation treatments and characterisation methods.

Christopher Dobbs is Head of Interpretation and Maritime Archaeology at the Mary Rose Trust.

For more information, please visit www.maryrose.org

THIS IS ENGINEERING
FASHION SPACE BIG STUFF ENTERTAINMENT SPORT
FOLLOW WHAT YOU LOVE INTO ENGINEERING
THISISENGINEERING.ORG.UK
THIS IS ENGI NEER ING

Metrology, the science of measurement, is increasingly being used in additive manufacturing. Renishaw worked with Robot Bike Co. on a highly engineered bike frame, which was constructed with titanium lugs (socket-like sleeves) that were created using additive manufacturing © Robot Bike Co.

MEASURE TO MAKE BETTER

Metrology, the science and technology behind measuring things, underpins all manufacturing. It is changing rapidly to keep up with the development of new production processes, such as additive manufacturing, and the demand for ever finer tolerances and quicker measurements. To meet these demands, engineers have developed new techniques, backed up by mathematical analysis and artificial intelligence. Michael Kenward OBE explored how it is already being used in manufacturing.

The National Physical Laboratory (NPL) estimates that more than £600 billion worth of goods and utilities every year are sold based on their measured quality

Measurement is fundamental in the production of just about everything. The National Physical Laboratory (NPL) estimates that more than £600 billion worth of goods and utilities every year are sold based on their measured quality. Without measurement, it is not possible to manufacture products efficiently, with a designed function, within specification and on cost. Measurement and verification typically account for 10% to 20% of production costs, an estimated £30 billion per annum in the UK. Metrology is also important in developing and policing the standards that underpin global trade.

The relentless pursuit of ever smaller dimensions and finer tolerances in products of all sizes is driving the development of metrology. As manufacturing moves to 'nano' (almost atomic) dimensions, scales between 100 nanometres and 0.1 nanometre, metrology must follow suit. The application of micrometrology and nanometrology to manufacturing is a key element of ultra-precision engineering. The goal is to achieve nanometre measurement accuracy on the manufacturing shop floor. Ultra-precision engineering is always seeking 'the next decimal place' or faster measurement of the current decimal place.

Research into precision engineering and the associated metrology includes: its fundamental philosophies; ultra-precision machine design principles and techniques; modern measurement techniques; optical design; and a wide range of inputs from nanotechnology. Precision engineering requires breakthroughs and sustainable solutions in the manufacturing and measurement of complex geometries, fusing nanotechnology into the macro world at the levels of accuracy generally called 'engineering nanotechnology'.

Metrology must also think big. Large structures such as those used in wind energy, aviation and ship construction require an increasing number of sophisticated and individualised large components, and require new approaches to metrology. For example, blades for wind turbines (now over 70 metres long) involve working to close tolerances that approach the limits of current small-scale manufacturing and production metrology.

One obvious role for metrology is in measuring, maintaining and recording the accuracy of machine tools on aerospace and automotive production lines, which are important manufacturing and export industries for the UK. The accuracy of machine tools determines the quality of the products they make. For the past two decades, researchers at the University of Huddersfield's Centre for Precision Technologies (CPT) have made significant improvements in measuring and compensating for machine tool inaccuracies, and for the temperature changes and vibrations on a noisy production line. An important part of this progress has been in the ability to carry out rapid geometric calibration and to use thermal imaging and flexible temperature-sensing strips to make accurate temperature measurements. A key application has been in the development of compensation systems for machine tools, such as large vertical turning lathes, to make them accurate enough to produce jet-engine casings at Rolls-Royce.

Live control of machines is not all that matters in manufacturing. Machine tools can consist of massive arrays of metalworking machines that operate on three axes. Setting up such a system can take time. One indicator of progress in metrology for such systems is in speeding up this set-up process. For example, research at Huddersfield has helped Rolls-Royce to reduce the average time for full machine calibration from days to hours [see *Quick change for machine tools* on page 22]. The ability to control machinery in this way has built on advances in collecting and processing data from accurate sensors. Temperature measurements alone are not enough: effective thermal compensation also relies on the ability to combine on-machine strain and vibration measurements with temperature measurements. Work on data fusion, and the development of new algorithms that bring together data from sensor networks, has become increasingly important in metrology.

AT THE SURFACE

Another important area of metrology is in the measurement of surfaces. While a surface might appear flat and smooth, measurement and characterisation can reveal a complex structure, often the result of factors involved in the manufacturing process. Surface size, geometry and texture are important in precision and ultra-precision engineering. Today's metrology can involve measuring 'features', such as the devices on an electronic chip or micro-electro-mechanical systems (MEMS) whose dimensions are similar to the texture of the surrounding surface.

Surfaces are also increasingly sophisticated. It used to be that the whole surface needed the same geometrical tolerance, but surface textures can now have the same size as important functional features. For example, if cylinder liners in a car engine are too smooth, the pistons seize up. The surface texture is important to allow oil to flow for

QUICK CHANGE FOR MACHINE TOOLS

Manufacturing depends on timing, not just the time it takes to make something such as a turbine blade, but the time that goes into setting up machine tools before production can begin. Rolls-Royce worked with staff from the Future Metrology Hub, based at the University of Huddersfield, on a project that helped to reduce the time needed to calibrate a five-axis machine tool used to make turbine blades from up to five days to less than two hours.

Rolls-Royce partners regularly with the Future Metrology Hub at the University of Huddersfield. The research carried out has developed the company's machine tools processes, for production of components such as jet-engine casings and gas turbine blades © Rolls-Royce

The research leading up to this improvement in set-up times was a part of the SAMULET (Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies) programme. Led by Rolls-Royce, the first phase of this collaborative initiative drew on the work of several universities on next-generation gas turbine technology. The overall project, which included the work at Huddersfield, ran for four years with a total budget of £80 million, and brought in Renishaw, one of the world's leading developers and suppliers of metrology systems. The research fed into the company's development of new metrology systems.

SAMULET considered several factors, including seasonal variations in working conditions. Temperature changes can affect the accuracy of machines tools, as can the need to adapt to the introduction of new products. One part of the work was to investigate different ways of monitoring temperatures. It turned out that thermal imaging is a valuable tool that can provide a lot of temperature information quickly, but it must be used with scientific rigour.

The research paved the way for better use of data captured by machine tools and their metrology systems. As in many areas of manufacturing, software plays an increasing role in these processes. One outcome of the research was a machine-tool calibration system that used methods based on artificial intelligence to optimise the measurement process and reduce downtime by a factor of 10 in manufacturing at large aerospace facilities. Monitoring data from machine tools can also help to reduce how long it takes to verify that the system is still correctly set up. Here the research, in collaboration with a team at the University of Bath, reduced verification times from 30 minutes to around two minutes.

lubrication. Metrology has to be able to measure that 'roughness'.

Next-generation products demand super-smooth surfaces, freeform geometries or even microstructures deliberately added to the surface to provide functional performance. Such surfaces include those used in optics in high-power laser systems or in earth/space-based large telescopes. Surfaces are also crucial in interfaces in fluid dynamics, such as energy-efficient jet engines, aircraft fuselages and wings. Increasingly important challenges in surface measurement include medical implants such as artificial joints, micro-electronics and MEMS machines, nano-electro-mechanical machines and in nanotechnology applications in general.

While it is important to be able to make precise measurements in the controlled environment of a laboratory, in manufacturing the real challenge is to make measurements at very high speed on a busy production line. The ideal is to use non-contact techniques with robust and accurate instruments that are as small and easy to use as possible and that can measure in real time and control the manufacturing processes. For example, industry is working on roll-to-roll approaches (creating electronic devices on a roll of flexible plastic or metal foil) to the manufacture of two promising new technologies, polymer solar cells and flexible electronics. These will need on-line metrology to detect and enable repair of defects. The same requirement already exists for the manufacture of current silicon-based photovoltaic solar cells. At Huddersfield, research has focused on detecting defects in the 40-nanometre-thick environmental barrier films for photovoltaic modules, where pin-holes in the film can allow water into modules, leading to electrical shorts and ultimately to the failure of modules.

Traditional approaches to surface metrology, mostly based on physical methods of measuring surfaces, cannot keep up with the demands of modern manufacturing. Stylus profilometry is the current state-of-the-art in terms of vertical measurement of surfaces, to quantify their roughness, with a tip scanning the surface. However, profilometry is a slow process and often cannot be used on soft or elastomeric materials, including many plastics and rubbers, or for materials that are prone to being scratched. These drawbacks rule out profilometry for optical surfaces, for example, and for nanoprinting, which is often on soft materials.

Modern approaches to surface metrology use non-contact methods such as interferometry, which uses electromagnetic waves, to carry out fast areal surface measurement of microscale and nanoscale surfaces. The most common of these is the scanning white-light interferometer (SWLI). Although one of the most flexible approaches, it is slow since the optical system must move through the vertical measurement range.

To alleviate the speed issue, researchers at the Engineering and Physical Sciences (EPSRC) Future Metrology Hub, based within the CPT, have developed interferometry devices with no mechanical moving parts. This provides the possibility of very fast measurement and the ability, through clever optical design, to make the instrument robust to environmental outside influences. One such system is based on the principle of wavelength scanning interferometry (WSI). The instrument has now become an industrial product, developed by the Centre for Process Innovation, IBS Precision Engineering and the University of Huddersfield and sponsored by the EU-funded NanoMend project. WSI is now used to detect the presence of

WITH ADDED CHALLENGES


The titanium lugs for Robot Bike Co.'s bespoke MTB bike frame were produced using Renishaw's selective laser melting process, an additive manufacturing technology that can build components directly from computer-aided design geometry using fine metal powders © Renishaw/Robot Bike Co.

Additive manufacturing, sometimes dubbed 3D printing, is becoming an indispensable component of the manufacturing toolbox for the aerospace, medical and automotive industries. Additive manufacturing opens up opportunities in the design and creation of novel shapes, and at small production runs. It can also use a range of materials to create products that are lighter and more efficient in their use of resources.

These attributes, and the geometrical complexity that it allows, mean that additive manufacturing brings new challenges for metrology. In its recent *National Strategy 2018–25*, Additive Manufacturing UK highlighted 'test and validation' as a priority area for the UK's high-value-manufacturing sector.

Additive manufacturing can create 3D structures that are beyond the scope of traditional metrology techniques where probes touch surfaces. This is why there are moves to use non-contact methods based on optical, electrical or magnetic measurements for example.

One example of additive manufacturing in action is the creation of frames for bicycles. Robot Bike Co. turned to Renishaw, which is involved in both metrology and additive manufacturing, when it wanted to make customised mountain bicycles. "We believe a bike should fit the individual," said Ed Haythornthwaite, the company's CEO. This meant customising the bicycle frame to each rider, which is where additive manufacturing was used. All the complex parts of the frame are made from titanium using additive manufacturing. These parts, along with more conventional carbon fibre components, allowed Robot Bike Co. to use innovative design approaches that avoided some of the failure mechanisms seen with other manufacturing techniques.

In additive manufacturing, metrology can happen in real time, in-line with measurement tools integrated into the nozzles and heat sources that lay down material, or off-line after production. On-line metrology can draw on fast imaging techniques, such as optical, X-ray, e-beam, ultrasound or scanning probes.

Techniques such as X-ray computer tomography (XCT) are now used measure the internal and external geometry of parts and even the surface roughness of features

microscale and nanoscale defects in coatings used to protect flexible photovoltaic cells, which are manufactured by roll-to-roll techniques. A demonstrator WSI system is operating on a pilot production line at the High Value Manufacturing Catapult Centre for Process Innovation.

ADDITIVE MANUFACTURING

Metrology must also keep up with the development of new approaches to making things. Additive manufacturing, for example, can create items with an infinite range of shapes and internal features that are not possible with conventional manufacturing techniques, such as milling, turning and grinding. The geometries are often free form and surfaces can be extremely rough, with various holes and internal spaces, which can create shapes that are beyond the scope of existing approaches to metrology. For example, additive manufacturing processes can 'print' freeform surfaces, with no obvious symmetry. How can an instrument measure surfaces that are inside these novel shapes?

In additive manufacturing, checking the geometry of parts as they come off a production line has moved away from the conventional coordinate metrology systems used in precision engineering. Techniques such as X-ray computer tomography (XCT) are now used to measure the internal and external geometry of parts and even the surface roughness of features. However, XCT is not yet fully traceable in a metrology sense. Measurement traceability describes an unbroken chain of comparisons, relating an instrument's measurements to a known internationally agreed standard. If traceability can be established, XCT should provide a way of assessing the conformance of parts made through additive manufacturing.

The process of additive manufacturing may also enable a different approach to metrology, measuring and controlling what is going on as each layer is added. Two techniques show promise in this area: infrared, or near infrared, thermal imaging of the melt pool and powder bed, and secondly, optical or ultrasonic scanning of the solid layers of the part as they build up. The hope is that, in the future, these optimised metrology systems will provide the basis for feedback control in additive manufacturing. Renishaw, which has its roots in metrology, is also increasingly involved in additive manufacturing and uses this approach in its processes.

The idea is to measure what is happening in the manufacturing process and use the data gathered as a measure of the finished product. However, one problem with this strategy is that the additive manufacturing process can create terabytes of data, too much to allow immediate analysis. The way around this is to look for anomalous signals in the data that indicate that something is going wrong. One complication with additive manufacturing is that by its very nature it is designed for smaller production runs, which means that there is a smaller archive of processing data for metrologists to draw on.

Additive manufacturing is not alone in creating novel surface geometries that need new approaches to metrology. Modern optical devices, such as cameras in mobile phones, no longer rely on symmetrical lenses. The rise of freeform optics, aspheric optics and diffractive optics require new measurement techniques.

QUANTUM LEAPS

Another challenge, and opportunity, for metrology is the growing industrial interest in the application of quantum technology, exploiting our understanding of the physics of atoms in materials and surfaces and their interactions with electromagnetic radiation of different frequencies. Quantum metrology exploits quantum phenomena – processes that show quantum behaviour at the macroscopic scale – to deliver new standards for time, frequency, length, charge and other key fundamental measures. The NPL has established a Quantum Metrology Institute, investing over £30 million including a £4 million equipment investment from the UK's National Quantum Technologies programme.

The ideal approach to measuring what goes on in production is to embed sensors into manufacturing processes. This requires miniaturised and affordable sensors that can collect data in dynamic situations. Many of these sensors use a combination of optical interferometry, structured light projection, and guided wave optics and quantum technologies. For example, it is now possible to create a complete optical 'system-on-chip' by integrating photonic devices on a silicon wafer, bringing together a tuneable laser, phase-shifter, wavelength de-multiplexer and wavelength encoder.

The importance of metrology for the future of manufacturing in the UK led to the creation of a new research centre based in the Centre for Precision Technologies at the University of Huddersfield. One of six new EPSRC-supported Future Manufacturing Research Hubs, the Future Metrology Hub will work with Sheffield, Loughborough and Bath universities, alongside NPL. Each research hub will address long-term challenges facing the UK's manufacturing industries, with a programme of innovative research in the engineering and physical sciences, related to the challenges in commercialising early-stage research. EPSRC will invest £10 million in the metrology hub while a large consortium of industrial partners has already pledged more than £30 million.

The current vision for metrology research is to develop the concept of the 'factory on the machine'. The idea is that metrology technology will make it possible to design, manufacture, measure and correct production in a single integrated system. Such an approach would create the essential link between design, manufacture and verification, leading to high-value manufacturing in digital, flexible, reconfigurable and autonomous factories. In this way, the 'right first time' factory could fabricate bespoke geometric products. The recent *National measurement strategy, 2017 to 2020*, from the Department for Business, Energy and Industrial Strategy, pointed to the general view in industry that we need more real-time, in-line measurement of manufacturing processes to allow process control, delivering right-first-time production and increased productivity, such as sensors on machine tools.

The strategy forecasts that this 'fourth industrial revolution' will see a rapid, powerful convergence of several big technology changes including autonomous vehicles, sensors, biotechnology, 3D printing, robotics and artificial intelligence. This vision for the future of manufacturing, sometimes billed as Industry 4.0, will naturally draw on the growing ability to capture the torrent of data produced by the growing portfolio of metrology techniques. However, there is no point in generating and capturing data for its own sake. The digital revolution may have brought with it the ability to generate, combine and manipulate huge quantities of data, but having more data does not necessarily increase its value. It is important to understand the quality, reliability and integrity of that data and to ensure that it leads to appropriate decisions.

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*.

Michael spoke to Professor Dame Jane Jiang DBE FREng, Director of the Future Metrology Hub at the University of Huddersfield, and Christian Young, Hub Manager.

WIND TURBINES PUSH METROLOGY TO THE LIMITS

Siemens makes 75-metre-long rotor blades at its new Green Port Hull factory. These blades, for 7 and 8 megawatt wind turbines, are individually made from fibreglass-reinforced epoxy. More recently, Siemens has introduced hybrid carbon blades. Different blade materials make it possible to tailor wind turbines for different locations, onshore and offshore and in areas with different wind conditions © Siemens

Manufacturing, and metrology, can come near their limits in the production of large sophisticated one-off components such as blades and mechanical components for wind turbines, which must be made to close tolerances, requiring careful control of production and quality inspection. Failure of the mechanical components in a wind turbine can lead to downtimes of days or weeks, especially for offshore systems where the weather can make maintenance hazardous.

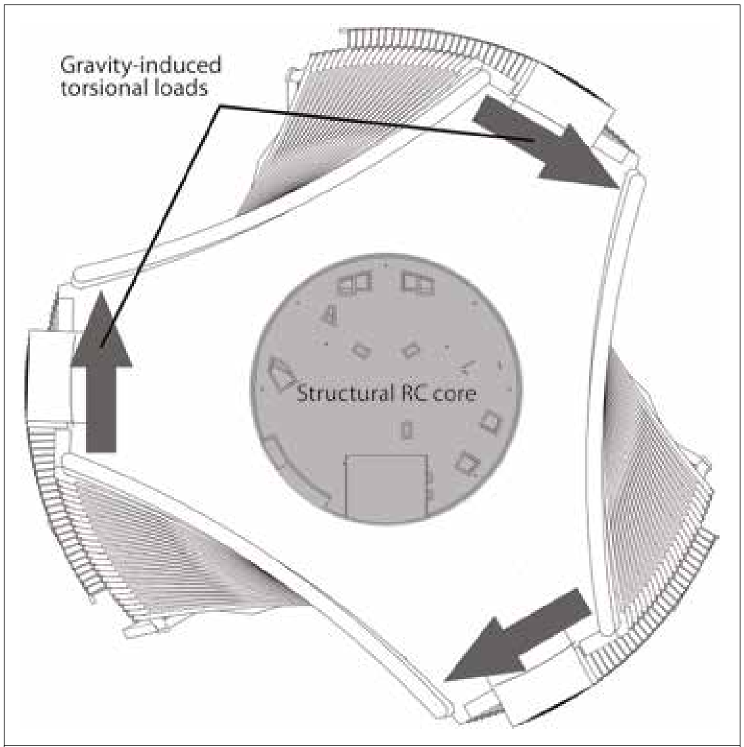
A further issue for metrology is in trying to measure the efficiency improvements that arise from new designs. There should be convincing field tests to confirm that those improvements are real enough to persuade engineers to introduce new designs.

As wind turbines increase in size – they already use some of the largest bearings produced – engineers must devise innovative technologies that integrate measurement processes into manufacturing. Structures such as wind turbines are often just too big to fit into conventional measuring devices or to be taken to a calibration laboratory, and must be measured in process or in situ. The need to make these measurements in an uncontrolled environment complicates the pursuit of accurate and traceable metrology to meet the regulatory pressures in many industries.

A TOWER WITH A TWIST

The PwC Tower in Johannesburg has a 1.2 degree twist over each of its 26 floors © Arup – Tessa Brunette

Building a conventional 26-storey building is pretty straightforward. However, twist it 30 degrees in a gentle spiral and a host of engineering challenges are created, from countering the huge torsional stresses to finding a way to clean the windows. Richard Lawson, Arup structural engineer responsible for the new PwC Tower in South Africa, explained to engineer and freelance writer Hugh Ferguson how modern computer systems helped to produce efficient solutions quickly.



The spiral form of the triangular tower induces a clockwise torsional load on the concrete core © Arup

Developer Attacq and its development manager Atterbury wanted an iconic building as the centrepiece of a new city district some 25 kilometres north of central Johannesburg. The architect, LYT Architecture, proposed a 26-storey triangular building with three concave glass walls – twisting clockwise (looking from above) as it rises from the ground. The twist aims to create an organic form, with the building looking more like a sculpture than a rectilinear block and creating the illusion that the building is rotating as it extends from its hilltop perch.

The concept is simple to describe, and even to sketch, but at the same time it introduces all sorts of geometrical and analytical complications. This is not the first twisted building – it is believed to be the 26th tallest of one form or another in the world, although the first in Africa. Here, the engineering team had to address the challenges without adding to the cost of construction and without compromising the office floor plans in a way that made them less attractive to tenants. "An engineer" according to an old American adage "can do for a dollar what any fool can do for two", and that was what the engineers had to do with the PwC Tower.

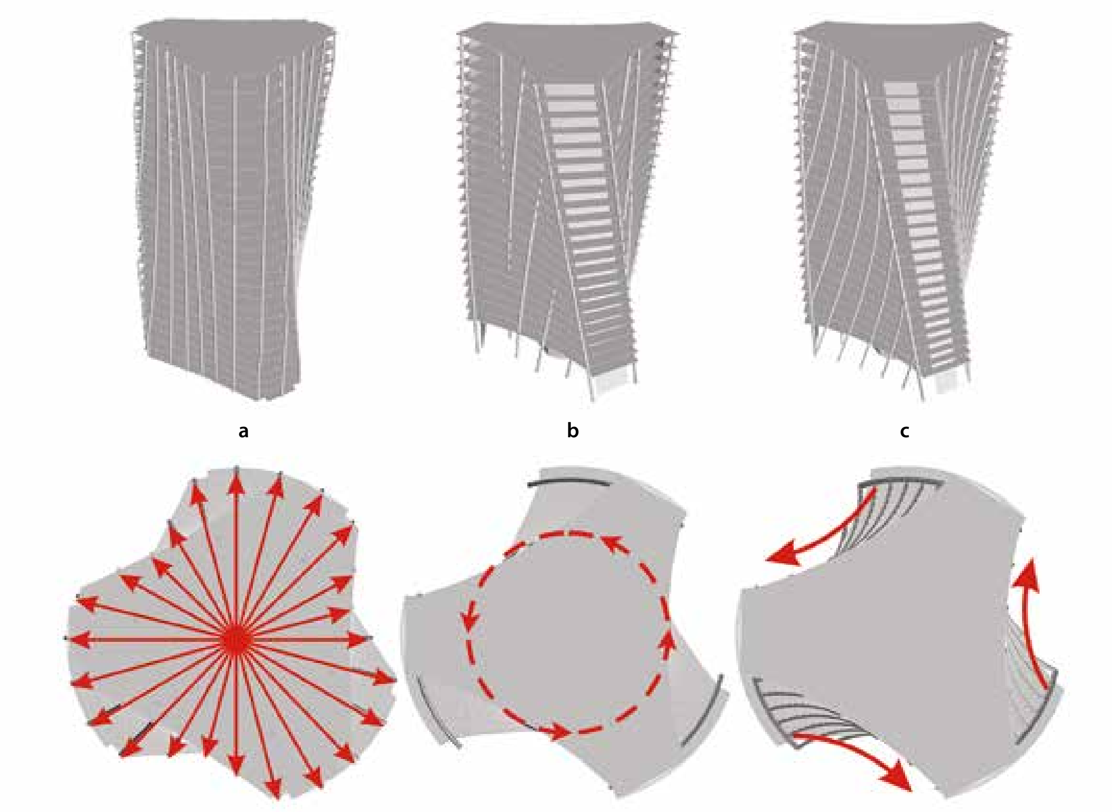
The biggest challenge was the spiralling form of the tower. A regular structural form that followed the twist of the building would create a clockwise torsional load because the building tries to fall in on itself. The traditional solution would have been to stiffen the cylindrical concrete tower that forms the central spine of the building, to resist the torsional load. Initial calculations showed that this would require a two-metre thick, heavily reinforced core wall. This would not have fitted in with the aesthetics of the tower, as well as taking up valuable space, and would have been far too expensive. Instead, the engineers proposed three alternative column arrangements that would reduce or counteract the torsion [see diagrams on page 28].

HANDLING THE LOAD

The first scheme was to avoid generating any torsion. If the twist was much smaller and the columns were all vertical, then varying lengths of cantilevered floors could make the building appear to twist while the structure did not. With greater twist, sloping columns could create the same effect, but ensure that all the structural columns slope away from or towards the centre of the building in a radial orientation. All lateral components of the axial forces in the columns therefore intersect in the centre of the building, while the structure, in effect, slopes away from or towards the centre, and consequently generates no torsion. Unfortunately, this idea resulted in an irregular pattern of columns that detracted from the building's spiralling form and did not fit with the aesthetics of the design.

The second scheme kept the columns at the ends of the building, which twisted clockwise with the form, but arranged the internal columns in an anticlockwise spiral, circular in plan, and with a diameter just small enough to ensure that the columns were entirely within the building. By placing the columns at the right slope it was possible to perfectly balance the torsional load from the end columns to eliminate, or at least drastically reduce, the torsional load on the core. It was easy to assess the required slope as each column was equidistant from the centre, so the 'lever arm' was the same. However, this scheme played havoc with the space planning: internal columns appear in different places on each floor, interfering with the usable space and requiring a different strategy for planning space for each floor.

The third scheme was similar, but with the columns pushed out to the facade of the building. This approach freed up the interior for flexible space planning throughout the building, with almost identical floor plans on each floor, but it also introduced additional complexity. Columns are curved in three dimensions up the height of the building to match the facade. However, each column actually comprises straight floor-to-floor sections, with slight angles introduced at each floor, and so the sections vary in both slope and orientation to the core. The columns intersect the floors at different distances from the centre, creating different 'lever



Plan and isometric sketch of each of the three alternative schemes for columns: (a) radially sloping columns; (b) internal spiral columns; (c) sloping facade columns © Arup

arms', and so each column exerts a different torsional load on the structure. The challenge was how to optimise the complex structure and, more particularly, how to optimise the slope and spacing of the columns, for structural efficiency as well as for aesthetic effect and buildability.

MODELLING THE TWIST

Manually setting up even one finite-element model would have been time-consuming: modifying the model to test many different slopes and column spacings would have been wholly impractical. The only feasible solution was to set up a finite-element model with varying parameters, and to choose the best model as the solution, which was less time consuming. Using parametric modelling software, the structural engineers modelled the tower's geometry in great detail. This was done in such a way that certain variable input parameters determined the geometry of the structural analysis model in Arup's well-established Oasys GSA analysis and design software, which calculated the stresses after the engineers had inputted the geometry and loads. The variables could include not only the column slopes and spacing, but also the number of storeys, the amount of twist per floor, and the radius of the arc of the concave glass facades, among other factors. Setting up the parametric model was time consuming, but subsequent analysis was fast and provided a useful tool for interchanging ideas with the architect: the engineers could use a 'slider' to vary one parameter [see *Parametric modelling*], revealing the implications almost immediately. The model also proved useful for other aspects of the design.

After many iterations, the chosen solution was five columns along the slab edge, and a 'repeat' of the column positions at the slab every five floors. This proved a satisfactory compromise between the various objectives. The configuration generated a torsion that countered 87% of the structure's gravitational torsion: the core carried the rest, but the reduction in the proportion of torsion it had to carry allowed the core wall's thickness to be reduced to just 450 millimetres – no larger than it would have been with no twist, and similar to many conventional buildings of similar height. The resulting column spacing of about eight metres matched the internal spans of the slabs and suited the basement parking layout. The arrangement also tied in with window mullions (the vertical bar between the panes

The chosen arrangement of columns under construction, with five across the width of the facade and repetition every five floors. Each column is spiral in shape, but made up of storey-height straight sections with changes of angle at each floor. The counter-sloping columns are purely architectural – to create a V pattern at the lobby level – and carry no loads © Arup of glass) and produced a form of symmetry that worked aesthetically and allowed considerable repetition for economy of construction.

Parametric modelling also helped optimise the design of the glass facades with their complex geometry: the short ends are both horizontal but not parallel and the edges are not necessarily at the same angle to the glass, while the long sides are not vertical or parallel in either frame. It would have been prohibitively expensive to produce glass curved in three dimensions to match the facade shape: instead the aim was to produce flat glass panels, and take out the curvature within the aluminium mullions (vertical) and transoms (horizontal) between the panels. It was decided to run the mullions parallel to the edges of the facades so that they were not actually vertical, with roughly constant spacing between mullions. The transoms were defined as horizontal at each floor level, and then the engineers used the model to test various mullion spacings to obtain a satisfactory compromise. The change of inclination at each panel had to be small enough both to maintain the illusion of continuously curving glass and to avoid excessively deep mullions.

The result was a series of storey-height (3.7 metres), prefabricated panels with flat glass but distorted mullion shapes to absorb the change of curvature: the panel widths are roughly 1.5 metres, but each varies slightly and is non-parallel [see *'facade panel'* image on page 28]. The chosen dimensions also suited the size of off-the-shelf sheets of glass, so glass wastage in manufacture was minimised. Each panel is different from its neighbour, but (by and large) the same combination of 24 panels is maintained on each floor of each facade, allowing considerable repetition for ease of manufacture and assembly.

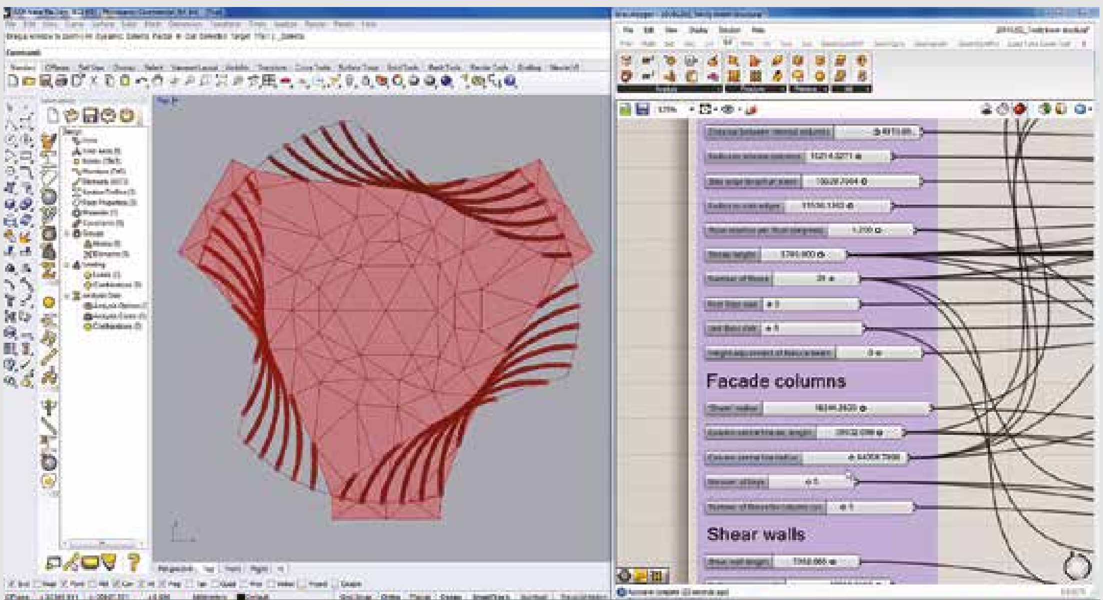
PARAMETRIC MODELLING

Parametric modelling allows a digital model of the geometry of a building to be created and then manipulated using a series of pre-programmed rules or algorithms – the 'parameters'. This enables engineers to evaluate the effects of changing some crucial elements of the design, quickly and simply.

For the PwC Tower, certain elements – such as the floor-to-ceiling height – were fixed. Then, the engineers created variable parameters within the model, including: the column slope; the column spacing; the number of storeys; the amount of twist per floor; the radius of the arc of the concave glass facades; and the number of facade panels across the width of each facade. For example, the slope of the columns could be changed by manipulating a 'slider' on the computer screen, the model would then adjust all other elements of the design to accommodate the change in slope, and the effect on the geometry of the building could be observed continuously on screen.

This helps the architects and engineers to judge what would, or would not, work aesthetically. The parametric model also provides input for more conventional software, including structural analysis software to calculate the stresses, and building information modelling (BIM) for communicating design information.

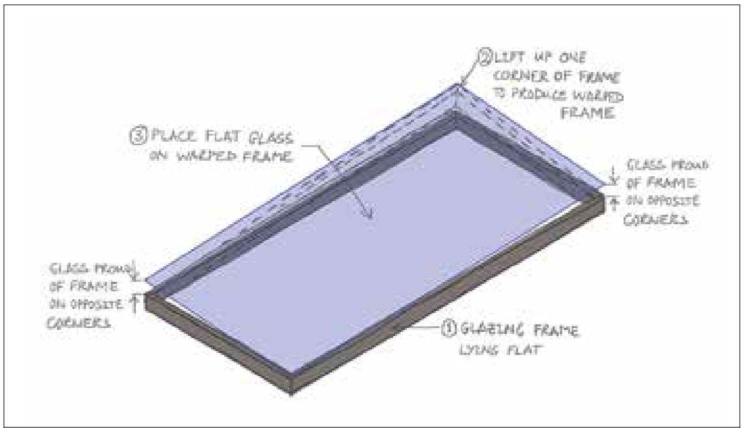
In this way, engineers can easily evaluate an infinite number of design variations, without having to go through the time-consuming process of re-inputting the data for each iteration.



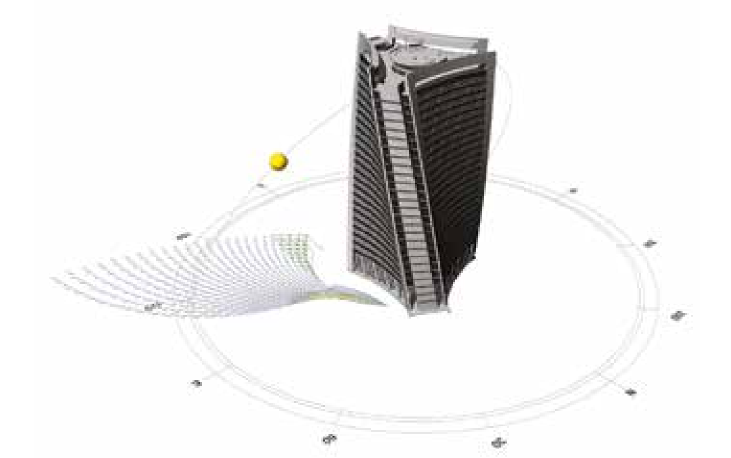
Parametric modelling is the modelling of a structure in n-dimensional space, where certain chosen parameters of the structure are variable. This allows the team to explore the impact of changing any of the input parameters on the design and cost of the structure, simply by moving a 'slider' on the screen © Arup

TACKLING 'HOT SPOTS'

Another complication of the glass geometry was the risk of concentrated solar reflection, the subject of several recent high-profile cases, notably at



Each of the facade panels is warped to accommodate the twist, but a glazing sub-frame within the panel allows the glass to be flat and sit in one plane. All of the geometrical abnormalities were cleverly hidden within the depth of the frame © Arup



Analysis of the concentrated solar reflection from the curved glass facades of the PwC Tower © Arup

20 Fenchurch Street in London (the 'Walkie-Talkie') where in 2013 plastic fittings on a Jaguar carparked nearby melted. There was no general analytical software for calculating the intensities of solar reflections, so the team developed its own purpose-built script and benchmarked it against other Arup studies from around the world. The modelling showed that the facade's shape could magnify solar energy at ground level by as much as six times the usual levels on a hot summer's day.

One solution would have been sun shades on the exterior of the building, but this was architecturally unacceptable and would have made cleaning more difficult. Instead, it was found that etching the horizontal bands of opaque glass in front of the floor slabs would reduce reflection, solving most of the problem. Any remaining spots with concentrations over two megawatts per square metre were addressed by landscaping to ensure that solar 'hot spots' could do no damage.

Another challenge was how to clean and maintain the exterior of the building. Without the twist, the conventional solution would have been to suspend a gondola by cables from rails at roof level. The simple solution was to retain the gondola, but add guide rails running down some of the mullions. These pull the gondola in to reach parts of the facade where the roof overhangs, and to push it out in other places, while guiding the gondola down the sloping mullions to reach parts not covered by the roof rail at all.

It was clear that the unusual shape of the building would lead to local concentrations of wind effects but assessing this from existing guidance was not possible, particularly the risk of deflected wind causing discomfort at ground level. Therefore, modelling was supplemented by wind tunnel tests in London. These assessed the concentration of wind loads at the edges of the facades (the corners of the triangle). The engineers addressed these by allowing a more economical sizing of the structure within the detailed design. At ground level, the tests revealed no wind problems in the sensitive areas around the entrance and lobbies, although they did identify some unexpected concentrations of wind nearby.

Construction of the building was complicated mainly because of the challenges of setting out the structure between points identified by three-dimensional coordinates rather than by conventional horizontals and verticals. Otherwise, design for buildability and close cooperation with the contractor meant that it was relatively easy to manufacture and assemble, particularly by the regularity and repetition of elements and dimensions. The core was constructed by slip-forming in a continuous concrete pour of 4,500 cubic metres over 43 days – a common practice in Europe but a novelty for office buildings in South Africa.

Richard Lawson stated that, by using clever design thinking and modern optimisation methods, the additional cost of the twist was a small premium compared with other iconic buildings. People moved into the PwC Tower earlier this year, and it is now the company's South Africa head office.

BIOGRAPHY

Richard Lawson is an Associate Director in Arup's Johannesburg office, responsible for the PwC Tower. The project team includes the client Attacq, development manager Atterbury, architect LYT Architecture, structure and facades engineer Arup, contractor WBHO, and facade fabricator Geustyn & Horak.

AN INGENIOUS INTRODUCTION TO ENGINEERING

Ingenious funds projects that aim to engage the public in engineering and encourage more engineers to share their experiences with wider audiences
© SMASHfestUK

The Royal Academy of Engineering's *Ingenious* scheme funds creative projects across the UK to engage the public with engineering. Now in its 12th year, it has funded over 200 projects and provided opportunities for more than 5,000 engineers to take part in public engagement activities that have reached more than 2.5 million members of the public. *Ingenia*'s Editorial Assistant Portia Sale talked to the organisers of five of the 2017 projects to hear about their activities, motivation and achievements.

With 2018 as the Year of Engineering, a government-led national campaign to inspire the next generation of engineers and widen the pool of young people who join the profession, it is now more important than ever to engage people with engineering. At the core of the Royal Academy of Engineering's *Ingenious* scheme is the aim to inspire creative public engagement with engineering projects, and motivate engineers to share their stories and expertise with wider audiences.

In a bid to increase participation by people from all backgrounds, the scheme prioritises projects that reach diverse and underrepresented audiences, including communities in the most deprived neighbourhoods in the UK. Research from a CaSE report suggests that young people from black, Asian and minority ethnic (BAME) backgrounds and children growing up in poverty are far less likely to enter STEM industries as a career. The *ASPIRES Report: Young people's science and career aspirations age 10–14*, published by Kings College London in 2013, found that girls, especially black students, are less likely than boys to aspire to STEM-related careers.

The projects that *Ingenious* funds creatively demonstrate engineering in all its forms, from a young inventors' club in a museum and a radio programme about railway infrastructure, to a touring STEM festival and a musical show that blends engineering with theatre.

> *The team spoke to primary school children about their ideas for the future of the railway. Their suggestions included everything from a carriage that was a cinema to a nuclear-powered train that would travel at super speed*

BRITAIN'S DIGITAL RAILWAYS

Britain's digital railways is a series of short radio programmes for children that explains how new construction and digital technologies are creating extra capacity on Britain's railways. Put together by Children's Radio UK, a 24/7 children's radio station, the short programmes explore different aspects of both historical and current railway infrastructure and discuss future engineering.

Creating inspiring content to introduce new ideas to children is nothing new to Children's Radio UK. Its earlier series have covered everything from art and chemistry to the ExoMars Rover and dinosaurs. The content is short: just three minutes to ensure that it can keep children engaged and effectively communicate a tiny part of a subject.

A conversation that Children's Radio UK had with Hitachi about its new high-tech trains inspired the project. The team realised that the trains were just a small part of the engineering involved, and that the task of building the tracks and infrastructure is just as important. It decided to create a series that looks at the infrastructure of railways rather than the trains themselves, exploring the impact of developing railways on people's lives and communities.

Including young engineers was a key part of creating the radio programmes. Children's Radio collaborated with Transport for London (TfL) and Network Rail to ensure that the engineering included in the programmes was up to date, and selected 10 ambassadors to help create the shows. Before recording the shows, the team spoke to primary school children about their ideas for the future of the railway. Their suggestions included everything from a carriage that was a cinema to a nuclear-powered train that would travel at super speed, and their ideas helped the team decide what type of content would interest them.

The series includes topics such as how to run more trains more often, tunnelling under major cities and building embankments in the countryside, rebuilding operational stations, electrification and alternative energy, and communications between trains. The series includes 22 three-minute radio programmes, each accompanied by an animated video.

Children's Radio UK also worked with the ambassadors to create media training workshops for over 100 young engineers and apprentices. The day-long workshops helped the participants learn how to research and prepare a talk, and develop their interview skills, as well as including practical time to record audio about their jobs and engineering experiences. The workshops have helped engineers to reach children, teaching them how to communicate their jobs to a young audience, and discover that their jobs fascinate and engage children. The team is releasing the interviews that the engineers recorded in these sessions as podcasts, aimed at a slightly older audience.

Children's Radio UK is now working on further engineering-related series: a 'how is that made?' series will look at production of everyday objects from the toothbrush to the carpet; a series exploring the opportunities to develop spaceports in the UK; and a new series focused on the 2018 Year of Engineering.

Britain's digital railways was launched on 19 February. To download the podcasts, visit **www.funkidslive.com/railway**

SMASHFESTUK: THE EARTH AND SKY TOUR


Participants at the Gloucester event with their new work ID cards © SMASHfestUK

The concept for SMASHfestUK grew out of Wyn Griffiths' idea of creating a mini festival for his wife Lindsay's birthday. Following the success of the event, the couple – working with Middlesex University and Lindsay's company The Refinery – wanted to organise a festival that could engage communities with science, technology, engineering, maths and the arts (STEAM).

After the publication of King's College London's *ASPIRES* report and the Warwick Commission's *Enriching Britain: Culture, creativity and growth* report, which both showed the lack of underserved and underrepresented groups progressing in STEAM subjects, the team decided to take its festival on a tour of disadvantaged areas in the UK. The aim was to break down barriers to social inclusion and STEAM engagement and focus on communities with multiple indicators for poverty.

SMASHfestUK works with local community groups, universities, schools, cultural organisations and young people to design festivals that are narrative-driven and entertainment-led, but include lots of STEAM activities. The team designs the festivals to appeal to parents just as much as younger audiences, creating intergenerational learning experiences.

In 2017, the festival imagined a world that has just been destroyed by a supervolcano, which allowed groups from all areas and backgrounds to engage in the topic. Participants helped to rebuild the world after the natural disaster, with a series of activities that used engineering to solve problems. The challenges included using scrap material to assemble structures, creating filters to provide safe drinking water, building piping and heating systems, and making rocket stoves from bricks. A core of engineers and scientists from universities and industry support the activities, as well as volunteers from the community. The Women's Engineering Society often sends volunteers, and SMASHfestUK ensures that its engineers represent a diverse range of ethnicities, genders and socioeconomic backgrounds, so that children and parents can meet engineers who they can identify with. A parent who attended said that it was "wonderful to see engineering really brought to life, with women engineers. Our daughter, and the girls in her class, will be inspired by this".

To discover the impact of the festival, the team measures both quantitative postcode and demographic data on attendance, as well as qualitative data about experience. An activity that resonates with many of the participants is making ID cards: visitors talk to the team about their aspirations and the job that they think would best suit them in a disaster situation, before creating their own professional card that includes their name, future job and photo. The activity is a way of integrating the earlier hands-on activities and embeds their aspirations into a meaningful artefact that they can take home.

The data has revealed that 62% of attendees were interested in STEM careers after attending the festival, with a further 18% interested in arts careers. Interestingly, in Gloucester a large proportion of attendees were interested in medical careers, while in Greenwich, visitors were most interested in engineering.

In 2018, its fourth year, the survival village will be dealing with the after-effects of a flood, the first scenario that may have affected attendees in the UK. SMASHfestUK hopes to get more engineering companies involved in supporting the project, to make it more sustainable in the long term.

For more information about SMASHfestUK and to find out where the festival will be next, visit **www.smashfestuk.com**


A young attendee at a SMASHfestUK event gets to grips with an activity © SMASHfestUK

TURBINES: A WIND-WIND SOLUTION

An attendee builds and operates his own wind turbine © Discovery Planet

A two-day event created by grassroots organisation Discovery Planet helped local people learn about the giant offshore wind farm near their homes. The organisation worked with the University of Kent and renewable energy companies Vattenfall and London Array to teach the community about one of the world's largest wind farms, located just off the Thanet coast in Kent.

The project took over a working café in Cliftonville, Margate, the fifth most deprived ward in England and home to a particularly diverse community. On the first day, Discovery Planet invited six local schools and home-educated children to learn about wind turbines through three different activities. On the second day, the café was open to everyone for free drop-in sessions. The University of Kent's School of Physics held six workshops about electricity and generation on each of the two days, and a retired engineer discussed renewable energy and designing wind farms. Participants had an opportunity to design and make their own wind turbine from a range of materials, including wood, paper, straws and beads. Volunteer engineers from various disciplines helped the children to work on and refine their designs, and they could test the turbines with a large fan. On another floor, there was a virtual reality experience that allowed participants to simulate climbing the stairs inside a wind turbine.

Volunteers from STEM Learning's ambassador programme and postgraduate engineers were available to answer questions about engineering, and the event coincided with International Women in Engineering Day. One participating volunteer said: "There were a good number of female engineers and scientists, such as myself, going around and speaking to the young girls and dispelling the myth that engineers and scientists are male. A number of girls said that they wanted to be scientists."

Discovery Planet tries to ensure that all its activities are free and accessible, and often uses empty shops or market stalls so that people stumble across the events. The events create a great opportunity for engineers to get involved in community outreach and the pop-up format is an effective way of reaching underserved audiences and presenting STEM activities in an unusual way. Discovery Planet has enabled other organisations, such as the University of Kent and Vattenfall, to conduct more outreach with disadvantaged communities. The local windfarm offers a good opportunity to connect the idea of engineering as a career with a firm example.

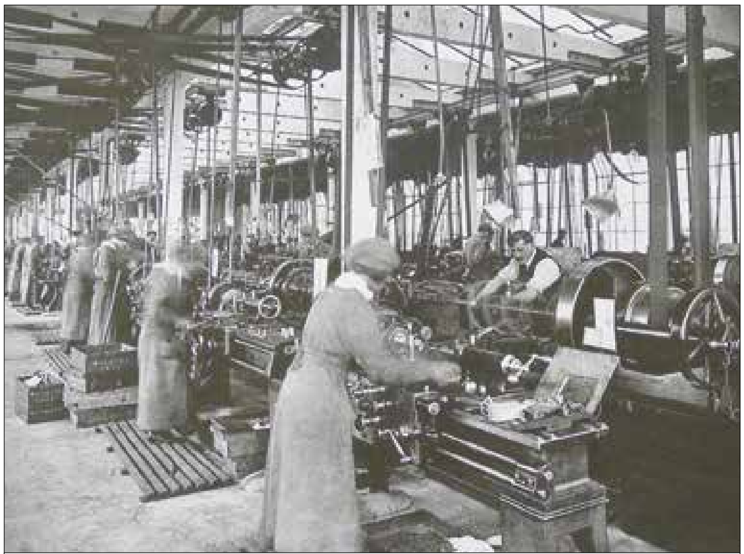
The organisation used feedback forms with both open and closed questions to monitor the impact of the event. Highlights included a changed attitude to engineering, stereotypes of engineering, and a better idea of how engineering affects people's lives. The feedback forms asked participants to describe engineering in three words after taking part in the event. Many of the responses contradicted stereotypes and included: "designing, creative, innovative"; "cutting edge, exciting, fun"; "amazing, special, curious". Working with engineers helped to change people's perception of engineering and what engineers do, with one commenting "I gained a better understanding of how engineering improves our lives".

The organisation's next event at pop-up stalls in Ramsgate Market will be all about genes. For more information, visit the Facebook page at **www.facebook.com/DiscoveryPlanetRamsgate**

School students try out the virtual reality experience © Discovery Planet

A CAR FOR WOMEN AND OTHER STORIES

Dorothée Pullinger with one of her Galloway cars © Le Couvey-Martin Family Archives



Women working at Arrol Johnston's Heathhall works © Le Couvey-Martin Family Archives

At the University of the West of Scotland (UWS), an interdisciplinary team of engineers, cultural theorists, filmmakers and media specialists are creating a film about engineering pioneer and local hero, Dorothée Pullinger.

Engineers Professor Katherine Kirk and Dr Evi Viza are working with filmmaker Tony Grace, cultural theorist Professor Katarzyna Kosmala, Dr Nina Baker, an independent women's engineering historian, and Neil Johnson-Symington, Curator at Riverside Museum of Transport in Glasgow, on the project about Dorothée's life and work. With Dorothée's local roots and history of championing women's involvement in engineering, she was an obvious fit for a film exploring women's engagement with engineering.

Dorothée's engineering career began at the age of 16, when she started working in a Scottish car factory. During the First World War, she managed 7,000 women munitions workers, before becoming director of Galloway Motors, which had an innovative apprenticeship programme for women. Here, she was integral to the production of the Galloway car – a smaller, lighter car for women that was not only designed for women but was built almost entirely by women. When the traditional engineering societies continued to reject applications from women, Dorothée became one of the founding members of the Women's Engineering Society, which is still inspiring and supporting girls and women to achieve their potential as engineers today.

The film is part of a three-year project that aims to inspire the next generation of women to pursue careers in engineering by revealing the untold histories of women engineers. The film will be a vehicle for the project to tell Dorothée's story, and will have an impact across different areas; as well as reaching engineers through exemplars of engineering, it is also providing creative opportunities for cultural and media students. The film has inspired UWS music MA students, who have produced songs written from the point of view of the women engineers who moved to Dumfries to work on the car.

This is the team's first STEM public engagement project and aims to promote a better understanding of engineering careers, including contributions from present-day engineers. It chose Dorothée as a character who would create strong public interest, but also enabled engagement with Scotland's industrial heritage. The team hopes that the film will help to change professional and organisational cultures as well as academic cultures and teaching. The aim is that the project will inspire further research into the area, uncovering more untold stories of women and putting them into the public domain. The project is included in the UWS prospectus, so is already encouraging the next intake of students to consider a career in engineering.

While various events have piloted sections, the full film is still in production. The project is being launched in June to celebrate International Women in Engineering Day, and public events across the UK will show the film to celebrate the Year of Engineering. It will be shown at the UWS campuses, Queen Elizabeth University Hospital in Glasgow and will be available to stream.

The workshop uses problem-solving to give participants the chance to be creative and address the challenges in their own way rather than through a list of instructions

KEEP CALM! I'M AN ENGINEER

STEM organisation 'science made simple' develops shows for schools, events and festivals. Its latest engineering workshop explores how people could use basic engineering to re-establish a post-apocalyptic world.

The science made simple team found that people who are deaf or hard of hearing are often an underserved audience, so wanted to create a fun, interactive workshop for audiences with hearing impairments. The workshop is based on Lewis Dartnell's book *The Knowledge*, in which the world as we know it has ended and survivors must start to rebuild civilisation. The book is a thought experiment that explores how to grow food, generate power, prepare medicines, and extract metal from rocks in a world with no modern conveniences.

The organisation wanted the workshop to reflect the book, but go beyond immediate post-apocalypse survival and focus on how engineering could rebuild society. It chose three key features that are essential for a functioning society – communication, power and transport – and worked with engineers to create activities that allow participants to use basic engineering principles to solve these problems. The workshop will focus on a scenario where the participants are trying to send a resource across the English Channel to other survivors in Europe. They will need to communicate their plan to those receiving the resource, design a mechanism to help them lift heavy materials, and build a boat to carry the resources across the English Channel.

A short animation without sound will introduce the workshop, and British Sign Language interpreters will help with activities to aid communication. The workshop uses problem-solving to give participants the chance to be creative and address the challenges in their own way rather than through a list of instructions. While science made simple usually puts on shows for larger groups, these workshops are much smaller, which allows the organisers to engage more closely with individuals and create more hands-on learning opportunities. As many schools are looking for increasing ways to integrate engineering and engineering-based activities into the curriculum, the workshops will visit six secondary schools, as well as festivals, where they will reach family audiences.

Science made simple has reached over 750,000 people in the 15 years that it has been running shows, and aims to inspire the next generation of scientists and engineers while engaging the wider public with STEM. The team constantly evaluates its shows to discover what sections and activities audiences enjoy most and least, and what they learned from the interaction. In its school shows, over 91% of pupils said that they had learned something and over 66% were more interested in science afterwards.

The *Keep Calm! I'm an Engineer* workshops will be taking place later in the year. For more information about science made simple, visit **www.sciencemadesimple.co.uk**

Several exciting and family friendly events are taking place across the UK in 2018 as part of the Year of Engineering **www.yearofengineering.gov.uk/inspired**

The Department for Business, Energy and Industrial Strategy supports *Ingenious*. It will be open for applications in the summer and offers grants between £3,000 and £30,000 for projects that engage the public with engineers and engineering. Find out more at **www.raeng.org.uk/ingenious**


Paddy Lowe FREng, Chief Technology Officer, Williams © Williams Grand Prix Engineering

Over the past 30 years, Paddy Lowe FREng has seen Formula One motor racing grow from small teams playing catch-up with engineering to a billion pound enterprise at the forefront of technology. In this time, he has introduced active suspension, hybrid engines and other key technologies that have changed the profile of motor racing. He spoke to Michael Kenward OBE about his career in this fast-moving industry.

A FORMULA FOR SUCCESS

When Paddy Lowe FREng started thinking about a career in motor racing, his first task was to find someone to send his job application to. Back in 1987, racing teams were not the household names that they have become, and there was no internet to search for contact details. Formula One (F1) motor racing had yet to achieve its global prominence or wealth, and engineering graduates were thin on the ground, which probably explains why only one of the three racing teams Lowe wrote to bothered to reply to a letter from the young Cambridge graduate. By coincidence, Williams, the company that did answer Lowe's letter, was near to the Oxfordshire site where he worked in the research and development (R&D) department of Metal Box, developing packaging machines. Today, Lowe runs Williams' engineering as Chief Technology Officer, and is one of the few engineers on the board of a motor racing business.

In 1987, when Lowe first contemplated motor racing as a career, the Williams team had won the season's F1 title, which it had achieved without much sustained engineering input. Graduate engineers were scarce in motor sport at the time and when looking for staff, Williams thought it needed more technicians. Lowe and Steve Wise, another young engineer who had contacted Williams, convinced Frank Dernie, then head of the team's R&D, that engineers, especially electronic engineers, might bring something to motor racing. They quickly proved the point. As joint heads of electronics, Lowe and Wise used their experience in control engineering to introduce electronically controlled suspension to F1. This engineering breakthrough helped Nigel Mansell win the F1 World Drivers' Championship in 1992.

Lowe fuelled the success by tapping into his work on packaging machinery, a world that might have seemed far removed from F1. At Metal Box, he had begun to develop an expertise in control engineering, an interest that started when he worked for the company on a gap year between school and university. Metal Box, which developed packaging machines for plastics and tin cans, sponsored a sandwich course so that Lowe could study engineering at the University of Cambridge.

LEARNING TO BE AN ENGINEER

Lowe confesses that he did not really know what an engineer was when he was at school. Like many people, he originally chose engineering partly because he liked to take things apart. With his brother Michael, five years his senior, he dismantled various engines and bicycles. Michael studied civil engineering at the University of Edinburgh before becoming a professor of mechanical engineering at Imperial College London, and is also a Fellow of the Royal Academy of Engineering. The Lowes are the only brothers who are Academy Fellows. "My mother is very proud of that," he laughs.

Lowe followed in his brother's engineering footsteps, but opted for a general degree course. When it came to picking final-year options for his degree, he drew on his time at Metal Box and chose control engineering. After graduating and a gap year sailing the Atlantic on a 12-metre boat, he moved back into R&D at Metal Box to work on real control engineering, a subject that Lowe still describes with enthusiasm. "You go and make things work. You close the loop." This all happened with some primitive electronics. "We were controlling things with eight-bit microcontrollers, or 16-bits if you were really lucky."

Packaging machinery might not seem exciting but it can push technology to its limits. The margins are so low that the business willingly invested a lot to keep production costs down. For Lowe, this was a way to get into electronic control systems and their use in complex engineering systems.

Lowe quickly discovered that in some areas of engineering, packaging was ahead of F1. When Lowe joined Williams in 1987, he jokes, F1 was something of a "couple of blokes in a shed" operation. "Back then there were few people in the industry who had an engineering degree; most were self-taught. It wasn't an industry that would

Nigel Mansell won the 1992 Formula One World Drivers' Championship in the Williams FW14B racing car. The car changed the shape of motor sport with its introduction of active suspension and traction control, two new technologies that Paddy Lowe helped to develop with expertise on control engineering that he brought to the team from his work on packaging machinery © Williams Grand Prix Engineering Limited

have appeared in the careers office." But that shortage of technical expertise meant that Lowe and Wise could bring their knowledge of electronics to a world that had previously been predominantly mechanical.

Lowe explains that, when they joined Williams, mechanical designers were devising new cars. "It was a very mechanical car," he says. "The only real electronics were from the engine side." That was down to Honda, which built the engines. "They were controlling the engine electronically, but there was nothing on the chassis. Anything to do with electronics, software or control, we started from scratch." They started with active suspension. "We got into things such as automatic gearshift. Then we did traction control and automatic race starts, so that includes automatic clutch control, active differentials, anti-lock brakes and so on."

A PLACE FOR IDEAS

It turned out that the F1 rules of the 1980s gave engineers a free hand in the technologies that they could deploy, but no-one had taken up the opportunities. Rules, Lowe explains, are the essence of motor sport. It is called F1 for a reason. "It is because there is a set of regulations. That is the formula." In the 1980s, the regulations set by the rule-making body, the Fédération Internationale de l'Automobile (FIA), were not very restrictive. "We had not exploited available technology within the regulations that existed. We were nowhere near the level of technology applied in other industries."

The door was wide open for engineers with ideas. "In those first few years that I

The only respite is in August, partly for the sake of family life, when the teams observe a self-imposed moratorium for two weeks. "No email, nothing," Lowe says. "It works really well. It is probably one of the best rules that we came up with!"

was at Williams, it was a bit like the Wild West. You could come in with an idea and you could go and just deliver it without any worry about regulatory limits." Lowe and his colleagues could spend a couple of weeks in the workshop and roll out a technology that they could try on a car immediately.

The development of active suspension illustrates what engineers could do with the freedom to innovate. Williams had been thinking about the idea before Wise and Lowe joined the team, but with them on board it could develop the idea further. Within a few years, the Williams team hit a winning streak when Nigel Mansell won the 1992 championship in the FW14B – "one of the more notable cars in F1 history," says Lowe. "That car was quick because it had active suspension and traction control." At the time, no other car had that.

Lowe still seems surprised by the gains that these engineering innovations delivered. "The traction control added one second a lap. The active suspension added about one second a lap, so we were basically two seconds a lap quicker than everyone else." Talk of seconds may seem like small gains, but that is far from the case. These days, says Lowe, when they come up with new ideas, F1 teams measure gains by the milliseconds they cut from lap times. For example, there was a big battle between Ferrari and Mercedes in the 2017 F1 series. "Those cars were trading places around one or two tenths of a second of difference."

With such small leaps in performance can F1 still be fun? "Absolutely," Lowe says "There are always new challenges. I have enjoyed every year more and more." It helps that Lowe now has a bigger role. He started off, as he puts it, "in the weeds of engineering, whereas now I have a much wider scope". The new challenge for Lowe is to do for Williams what he has done with other teams. Like drivers, engineers sometimes move between teams during their careers. Lowe was at Williams between 1987 and 1993, then he moved to McLaren Racing as Head of Vehicle Technology. After filling several roles with that team, he moved to Mercedes in 2013 as Executive Director (Technical) for four years until the call to return to Williams came in 2017.

What prompted the move? At Mercedes, Lowe had overseen three consecutive Drivers' Championships and three consecutive Constructors' Championships, a measure of the performance of key elements in a team. In contrast, after dominating the sport in the 1980s and 1990s, in recent years, Williams had rarely made the winners' podium. "It was just a great opportunity for me to come in at a senior level and to see if I could help bring the team back to the front of the grid."

MAKING A RETURN

Lowe rejoined a team with many more engineers and a brilliant fanbase. Williams now operates on a modern campus. As Chief Technology Officer, Lowe runs engineering at Williams F1, which employs around 650 staff, plus another 250 people at Williams Advanced Engineering. The group also includes a conference centre and museum of historic cars. Within the F1 team, separate groups cover different aspects of engineering. "The biggest performance area for the team is aerodynamic performance," says Lowe. A technology department in its own right, the aerodynamics engineers run a wind tunnel and have a high-powered computer for computational fluid dynamics (CFD). "The output from the aerodynamics department is a set of surfaces, which they have defined using their toolsets, the tunnel and the CFD." Most F1 teams buy in engines, and in Williams's case they come from Mercedes. However, teams typically design their own chassis and gearbox. This all feeds into the design of each season's new cars.

When it comes to race season, the pit team is a mix of about 50 engineers and technicians. "The technicians do the logistics and build the cars: the engineers are there to exploit a car to be the best," says Lowe. "We have a lot of experts on different topics. Tyres, aerodynamics, brakes – all have their specialists, along with engineers who monitor the mass of data gathered from the cars' electronics."

Lowe's job as Chief Technical Officer is to tie everything together, as well as the all-important task of determining the race strategy. "What tyres will you put on? What do you want each driver to do? You have to choreograph what you want to do with the cars. The pit stop is a great example of that," he says. "The actual execution of the pit stop is a very technical process as well as an interesting team process." On top of that, Lowe looks for lessons to take home to improve performance before the next race. "You are working across multiple time frames. You are trying to optimise what you have on the day, but you are always looking to what you can bring to the next race. Then also what can you bring to next year." This is why TV viewers see Lowe in coverage of F1 races with his headset on, scrutinising monitors as they collect data from the cars.

Teams spend a lot of time on the road. The race season has grown and now runs from March to November. There are usually races every other weekend, along with two or three 'double headers' with races on consecutive weekends. The 2018 season has the first triple header, with races three weeks running. The only respite is in August, partly for the sake of family life, when the teams observe a self-imposed moratorium for two weeks. "No email, nothing," Lowe says. "It works really well. It is probably one of the best rules that we came up with!"

As head of technology at Williams F1 racing, Paddy Lowe (centre) is in the pits on race day, analysing the cars' telemetry data, choreographing what goes on in the team's two cars, and looking for possible improvements for future races and the next season's cars © Williams Grand Prix Engineering Limited

FORMULA ONE OF THE FUTURE

Those FIA rules, which Lowe has helped to set for some years, provide F1 teams with a moving target. "The rulebook is an awful lot thicker and you very rarely find a new opportunity within the regulations where the engineering has not yet been pushed to the limit. Today, we are operating at the limits of the rulebook and the limits of technology, compared to 30 years ago when we were operating at the limits of our capacity and capability." The engineering in F1 is now also far more objective, he adds. "It is based upon the use of sophisticated analysis and simulation tools. We used to just guess at performance. Now we can calculate what we are going to gain from any particular prospective design or candidate design."

In 2014, another change in the formula that appealed to Lowe was the requirement in the F1 rulebook that mandated hybrid engines for cars. Lowe was running technology at Mercedes when this happened and oversaw the team's move to hybrid engines. "These V6 engines are now around 50% thermally efficient," he says. Thermal efficiency is an important aspect that modern engine builders must consider. It is calculated on the amount of useful energy that can be produced from the heat supplied to the engine, without having to recover energy under braking. Lowe says that it is "incedible" that the hybrid engines are delivering 50% thermal efficiency at constant speed.

The new formula set out to encourage fuel efficiency. F1 cars are limited to 100 kilograms of fuel an hour. "Clearly, the more power you can make from your 100 kilos an hour, the quicker you will go." This is also an efficiency measure. "In 2014, our engine was about 45% efficient, so you can see that, in three or four years, the regulations have driven us within F1 – using our technology, our capacity, resourcefulness and a motivation to win – to increase thermal efficiency of a combustion engine from 45% to 50%. They didn't manage that in the previous 100 years of automotive industry."

Lowe does not claim that F1 is a test bed for technologies that can end up in showroom vehicles. "If you dive into that engine and ask yourself how much of it applies to a road car, you might find maybe not all that much. But the point is that we have shown the industry that you can get 50%, maybe not using exactly the same methods that we have used, but you know that that is a good direction." Then there is the effect on the millions who watch F1 on television. "You make the hybrid engine more of an aspirational technology rather than something quite dull, which it might have been before."

There are other ways in which F1 can benefit engineering in general. For example, the work in wind tunnels can deliver technologies that can apply not just outside F1, but outside motoring. The group created Williams Advanced Engineering for exactly that purpose. "It makes use of technology and skills that we have developed for

With more than 44,000 Twitter followers, Paddy Lowe is one of the UK's most visible engineers
© Williams Grand Prix Engineering Limited

our F1 programme, applying it to other industries." One such development, carried out with another startup business, Aerofoil Energy, takes the company's understanding of aerodynamics and expertise in CFD to develop aerofoil systems that keep cool air inside a supermarket's refrigerator cabinet, delivering significant energy savings.

Nearer to the car market, Lowe is enthusiastic about the work that Williams Advanced Engineering is doing on electric vehicles. "We build electric vehicle prototypes for several large automotive companies." Car companies can also buy into the company's FW-EVX 'platform concept' for electric vehicles. The electric vehicle technology includes innovations in battery pack design, cooling systems and lightweight structures, all brought together into a single platform that car makers can adapt to meet their own needs. This takes in the expertise of the F1 engineers in aerodynamics, electric systems, advanced lightweight structures and vehicle integration.

One area where the new business has already made a significant impact is in batteries for electric vehicles. "I think that electric cars are coming quicker than anybody thinks," says Lowe. They are even making their mark on race tracks, in the shape of the Formula E series, an electric version of F1. "We build all of the batteries for Formula E," says Lowe. "We run a Formula E team on behalf of Jaguar."

Lowe highlights the importance of the engineers' ability to tackle batteries at the systems level. "It is one thing to build batteries, but then to build an effective battery management system and a thermal solution for batteries is where it gets difficult." It is all very well demonstrating great performance in tests, but it does not mean much if everything gets so hot that it has to be left to cool down for a long time. "A Formula E car is being driven flat-out all the time. Formula E has been a very valuable exercise in improving what we can do and what needs to be done in that area." Williams is also involved in the UK's Faraday Battery Challenge, a multimillion pound R&D effort managed by Innovate UK and the Engineering and Physical Sciences Research Council.

These moves to the frontiers of engineering are just one sign of how much has changed in Lowe's 30 years with F1. It took a lot of money to make that transition. As a business, F1 has grown at compound annual growth rate of 8% to 10% in the sport's income and spending. This is, says Lowe, an incredibly successful industry to have grown at that rate for a 30-year period.

The success of F1 is well understood in the engineering world, and it is held up as a sign of Britain's engineering prowess. This explains why F1 now has no problem recruiting graduates. "We are fortunate in that we are able to attract very high-calibre recruits. You can work on a great technology, reasonably well-resourced and funded to do so. You see the results on TV every two weeks. It is tremendously rewarding." Lowe would like to use that excitement to spread the word to a bigger audience. "If there were ways to leverage the excitement of F1 as an engineering destination, more effectively into schools, that would be great."

Social networks play a part in Lowe's efforts to spread the word about engineering. With more than 44,000 followers on Twitter, Lowe is one of the more visible engineers in the country, perhaps even globally. This visibility is understandable given Lowe's role in, by the latest count, 158 race wins, seven Drivers' Championship titles and five Constructors' Championship titles. The enthusiasts are always looking for clues as to what is in store for the next racing season. The fans will be kept guessing until the season starts in March, with one report suggesting that fans can expect gradual change, while another tells them to look out for "substantial changes". Lowe did give *Ingenia* some insights into the new cars: "We are doing a car that is quite different for next year than it was this year. We hope to be substantially quicker." However, he did not volunteer how many milliseconds he hopes to shave off lap times.

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, **1962**. Awarded a degree in engineering from the University of Cambridge, **1984**. Worked in R&D at Metal Box, **1985–1987**. Joint Head of Electronics, Williams, **1987–1993**. Various roles at McLaren, including Head of Vehicle Technology, Chief Engineer Systems Development and Engineering Director, **1993–2013**. Executive Director (Technical) at Mercedes, **2013–2017**. Fellow of the Royal Academy of Engineering, **2015**.
Chief Technology Officer, Williams, **2017–present**.

INNOVATION WATCH

A MORE CONVENIENT WAY TO CAMP

In 2004, a small British manufacturer produced a tent that weighed less than a kilogram. Since then, Terra Nova Equipment has continued to push the boundaries of camping technology, and currently holds the world record for producing a 500-gram tent – the lightest that is commercially available.

Andy Utting, a civil engineer and Managing Director of Terra Nova Equipment, set the challenge of producing the world's lightest tent after noticing a growing demand from solo hikers who wanted to reduce the loads they carried. As an outdoor enthusiast himself, he was also tired of lugging bulky and heavy equipment on overnight trips.

Producing such a lightweight tent required years of experimentation, innovative materials development, refining of manufacturing processes and clever design work. Utting and his team's first step was to look at the materials they were using. Previously, Terra Nova had established a reputation for producing sturdy mountain tents that withstood nights on end in inhospitable places such as Mount Everest. The team evaluated the tents, and found that the pegs and poles were the heaviest components. Tent pegs alone can weigh up to 300 grams, so swapping to titanium and reducing their size immediately helped to decrease the weight, as did switching to finer zips.

The team attached stress gauges to the tent poles to measure the strain that they were placed under. This revealed that, as the poles were forced into place, they came under extreme loads often well beyond their expected limit. Decreasing the weight of the poles might have helped save weight, but would increase the risk of them breaking as a user wrestled them into place, especially in windy conditions. However, tests showed that by pre-bending certain sections the team could reduce the stress the poles came under. They also used an odd number of poles to ensure that there was no join at the top of the curve where stress would be greatest.

The pre-bent poles could then be made thinner and lighter, but the team also discovered that the strength of a pole was more dependent on the diameter of the tube rather than the thickness of its aluminium walls. By increasing the diameter of the hollow poles by just 0.2 millimetres, they could maintain the strength but reduce weight.

The fabric of the inner and outer skins of the tent were another area that could be transformed. Initially, the team began by reducing the fibre thickness (denier) of the polyester and nylon used to weave the fabrics, but to make the lightest tents in the world, they needed to look for new materials. They discovered that instead of using woven fabrics, they could use a technology more commonly used to make ropes and reinforce body armour – ultra-high-molecular-weight polyethylene.

This thermoplastic can be spun into fibres that are then aligned and bonded together to form thin, flexible sheets. By laminating a single sheet on both sides with a thin polymer film, Terra Nova created super thin and waterproof fabrics. Titanium dioxide, which is often used in suncream, was added to the final coatings to help protect the fabric from damage caused by ultraviolet light.

Terra Nova's years of research and development into innovative materials led to the creation of the world's lightest tent

Terra Nova also changed how the fabric was joined. Sewing tents together adds weight from the thread as well as the layers of sealant needed to ensure that water does not leak through the holes left by the needle. Instead, the team bonded the seams together using tape that is heated to fix two pieces of fabric together. Tests showed that the bonds created in this way are stronger than the fabric itself, so the seams were no longer the tent's weak point.

These weight-saving innovations culminated in the Terra Nova Laser Ultra 1, a tent that weighs less than a half a kilogram. Now, the company is looking towards a new challenge. The current focus of the outdoor industry is to reduce the pack size of equipment too, so Utting and his team are hoping to use their knowledge to create tents that will be not only the lightest, but will also take up the least room when thrown into a backpack for an adventure.

Words: Richard Gray

HOW DOES THAT WORK?

ROBOTS

While there are many different types of robots, which perform tasks as varied as space exploration, shelf-stacking and surgery, they still have core features in common. A robot can sense its environment, plan an action and then carry out the action.

Robots are generally made up of the same components: a movable physical structure, a motor, a sensor system, a power supply, and a computer to control the processes, which can be an external device or internal control system. Robots vary between being autonomous, semi-autonomous or manually controlled, and may have a humanoid form or be designed for a specific task.

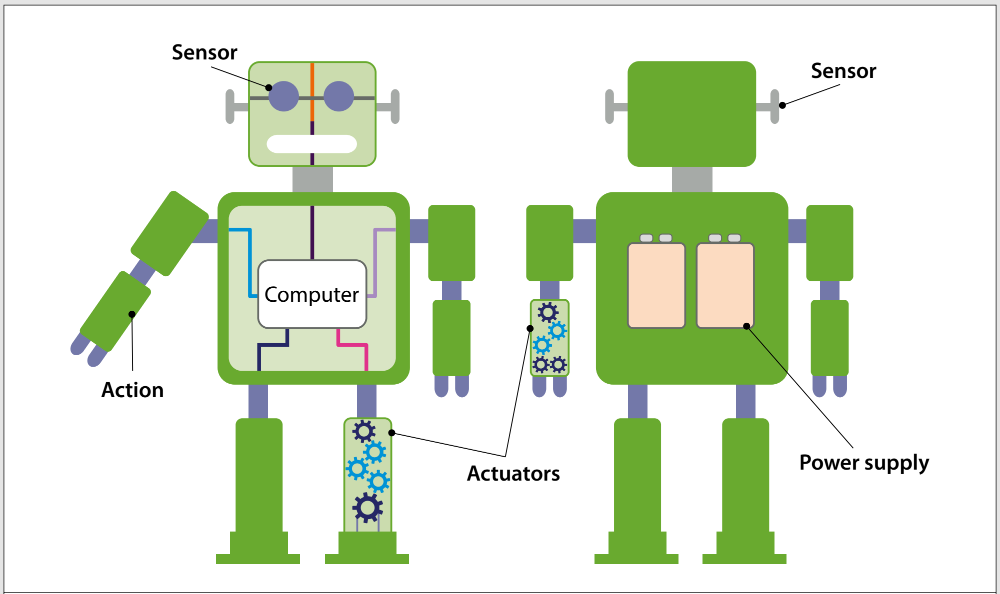
The actuator is the part of a machine that moves and controls parts of the system. The actuators connect to an electrical circuit, which powers the electrical motors and electromagnets directly or activates a hydraulic system through electrical valves.

In robots, the actuators are powered by a battery, solar power or mains power supply, and are usually one of the following:

- Hydraulic – hydraulic actuators have a cylinder or fluid motor that uses hydraulic power to create motion. As they are powered by liquid, which cannot be compressed, hydraulic actuators exert a large force.
- Pneumatic – pneumatic actuators use pressurised air to create movement, converting energy formed by a vacuum. This system enables considerable forces to be produced from relatively small changes in pressure.
- Electrical – motors power electric actuators to convert electrical energy into movement. These are more precise, quieter and easier to reprogramme than hydraulic or pneumatic actuators.

The actuators are attached to an electrical circuit, which powers the electrical motors that activate them. For example, a hydraulic system is activated by manipulating electrical valves that drive the compressed fluid's path through the machine. Then, to move a hydraulic arm for example, the robot's controller would open the valve leading from the fluid pump to a piston cylinder attached to that arm. The fluid would extend the piston, swivelling the arm. To move their segments in different directions, robots use pistons that can push both ways. The robot's computer controls everything that is wired to the circuit.

Engineers programme the computer to switch on the relevant motors or valves to carry out pre-planned tasks. Algorithms for specific tasks are programmed into the robot, which send the correct signals to the actuators.



A robot's core components allow it to sense its environment, then plan and carry out an action

Different robots use a variety of sensors, such as a photodetector and microphone help to identify light and sound, facial recognition systems to identify faces and ultrasonic transducers to detect how close an object is. While some robots can see and hear, most have the ability to sense movement. A simple design to allow a robot to sense its own movement incorporates slotted wheels on the robot's joints. Beams from an LED light shine through the slots, and a sensor on the other side reads the pattern of flashing light as the wheel turns, sending data to the computer to analyse how far the joint has moved based on the light pattern.

Robots are already carrying out tasks in many industries, including healthcare, manufacturing, research and military, and look set to have further applications in many more.

Engineering excellence

Helmet-mounted displays that help pilots see the big picture in the most challenging situations, submarines that stay undetected for months at a time, the UK's biggest ever aircraft carrier – it takes engineering excellence to deliver an essential advantage. We encourage and develop this excellence across our diverse workforce around the world so we can keep advancing for our customers.

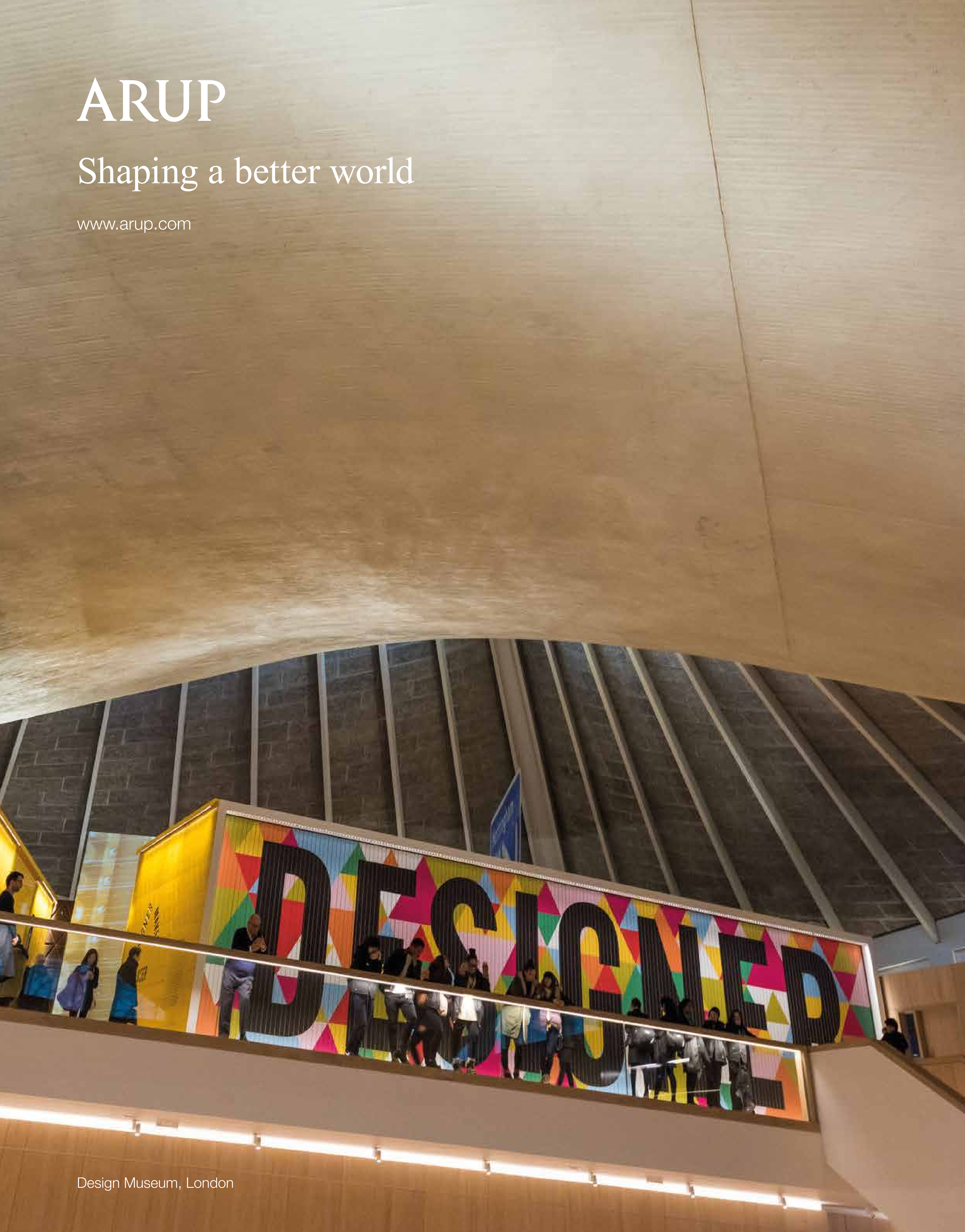
www.baesystems.com

BAE SYSTEMS
INSPIRED WORK

ARUP

Shaping a better world

www.arup.com



Design Museum, London