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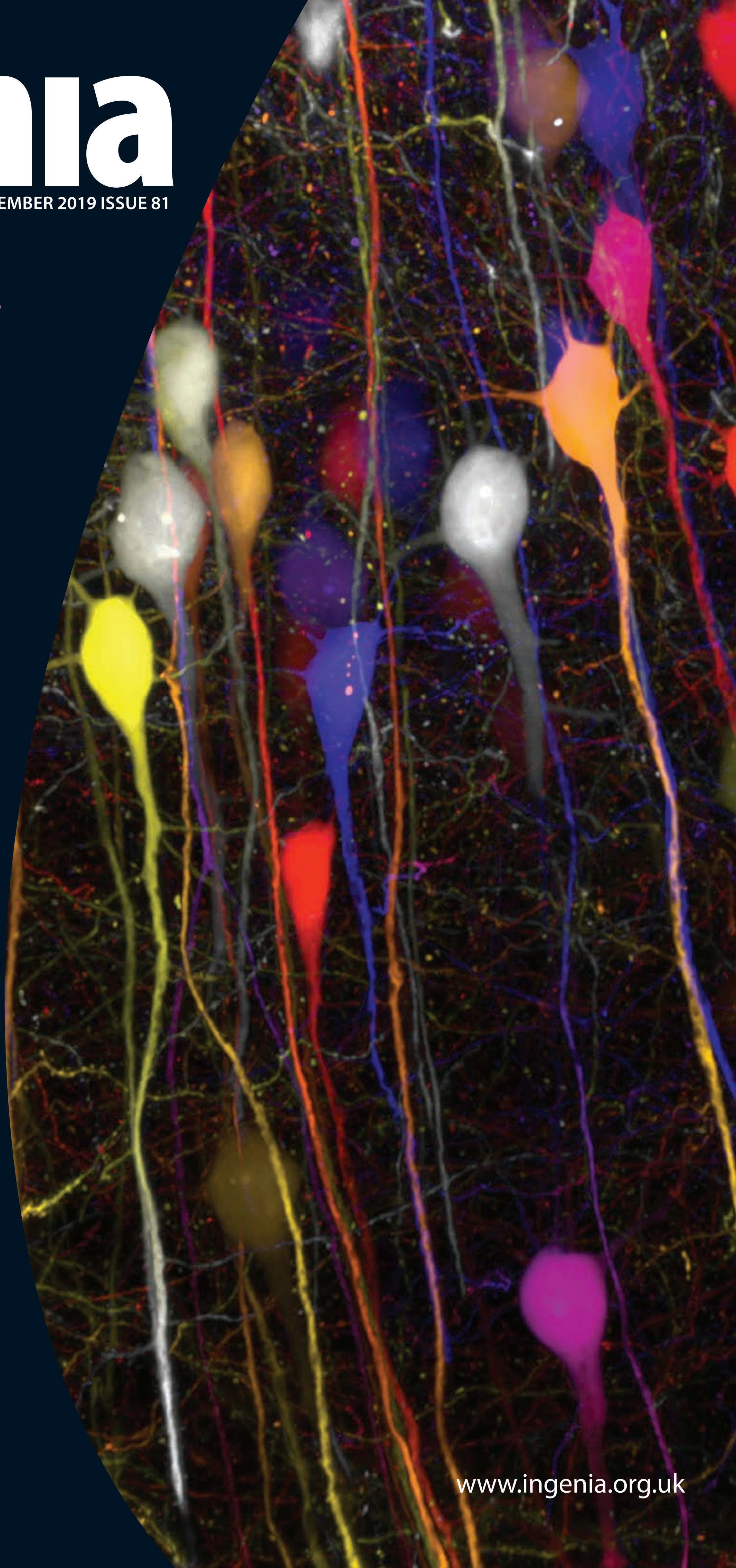
DECEMBER 2019 ISSUE 81

COMPLETING THE SAGRADA FAMÍLIA

MARS EXPLORATION

LIVERS ON THE MOVE

QUANTUM LASER LEAP



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Front cover
The engineering behind the M Squared SolsTiS supported the development of microscopes, here showing an optically cleared mouse brain projected using a coloured height map © Dr Anthony Vernon and Robert Chesters, King's College London.

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


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EDITORIAL

THIS IS SPECTACULAR

Scott Steedman CBE FREng

In under two years, teenagers have notched up more than 36 million views of the short *This is Engineering* films. This digital marketing campaign (thisisengineering.org.uk) is a spectacular success by any measure, an exemplar of what the profession can achieve when it works together to communicate a single message, that engineering can be a rewarding, future-shaping career that can change the world. Changing the public perception of what it is to be an engineer has been an ambition, and an uphill struggle, for many years – now it is starting to happen.

The films showcase young engineers talking about what they do across a vast range of careers: fashion, film, sport, space, environment, health, helping people and even 'big things', to list just a few of the subjects covered. They are inspiring.

Ingenia flagged up the launch of *This is Engineering* in 2018 (*Ingenia*, Issue 74). On 6 November the campaign stepped up a gear to become the driving force behind the first *This is Engineering* Day. It was a day to celebrate what engineers do for the world: the media loved it. Working with EngineeringUK and other professional engineering institutions, the Academy achieved remarkable coverage in the press and social media, including interviews on the BBC and tweets from astronaut Tim Peake (1.6 million followers) and Academy Honorary Fellow Lewis Hamilton (13.4 million followers).

The biggest change this year was the backing of household names from Amazon and Ocado to the BBC and Facebook, which all depend on engineers to make their businesses work, in addition to the corporate partners who have made the campaign possible since its inception. Over 136 organisations have pledged to present to the public more representative images of engineers and engineering and for the rest of us, there is an excellent free-to-use library with over 700 images available for download (flickr.com/thisisengineering).

Behind the razzmatazz there is a growing sense of urgency. EngineeringUK has calculated that the UK faces a shortfall of tens of thousands of engineers each year. Only 12% of professional engineers are female and just 9% are from black, Asian and minority ethnic backgrounds. With engineers from all backgrounds in such demand, choosing an engineering degree, vocational course or career path should be very attractive, but moving the needle is much easier to say than to deliver. Having landed the brand with the media, companies, universities and teenagers, it is time to link it into the great issues of the day, to focus on the outcomes that engineers and engineering produce.

There are many important issues of the day where engineering is crucial, but one stands out as a candidate to connect much more to engineering through the campaign. Respected globally, talked about constantly, the UN Sustainable Development Goals (SDGs) are increasingly visible in corporate literature, in the media, in conversations with the next generation, everywhere. There are 17 goals, covering challenges including zero hunger (goal 2), affordable and clean energy (goal 7) and industry, innovation and infrastructure (goal 9). All of the SDGs will require engineers and engineering. This will be a global journey, but one where UK engineers could and should take a leading role.

We know that young people are increasingly aware of, and interested, in the challenges of the future, especially climate change. Some have even taken to the streets to show that they want to do something to protect their own futures. What better way to encourage them to deliver impact than to choose a career in engineering?

We have caught their attention with an excellent marketing campaign, but what next? We need to show our audience where engineering could take them. Within a few years, the SDGs will become woven into the fabric of organisations and government action around the globe. There is a huge opportunity for the Academy and its partners in *This is Engineering* to set out the connection between engineers, engineering and the SDGs. Whether it is responsible consumption and production (goal 12) or climate action (goal 13) that the next generation is interested in, *This is Engineering* could play its part. 'Want to help shape the future?' shouts the banner on the website. *This is Engineering* has proven that it can hit the headlines. Now let's see it take off.

Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

SENSORS TO PREVENT SEPSIS

George Winfield won the JC Gammon award, which offers training and networking opportunities to help grow his business

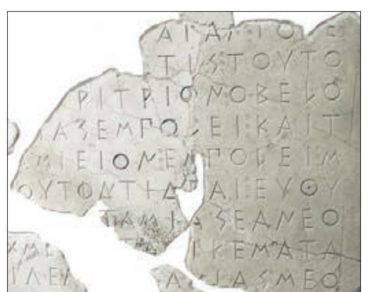
In October, a technology to help detect sepsis was awarded the JC Gammon award. George Winfield, Founder and CEO of Spyras, won a £15,000 prize and support from the Royal Academy of Engineering Enterprise Hub.

Every 3.5 seconds someone in the world dies from sepsis and earlier identification of the condition could save up to 14,000 lives a year in the UK alone. Spyras has helped develop breathing analysing technologies that could enable improved monitoring of hospital patient's breathing and help detect sepsis.

One of the early symptoms of sepsis is rapid breathing. Currently, breathing rate in hospitals is measured by manually counting the rise and fall of a patient's chest. Spyras, using a range of technologies, such as paper-based sensors, could monitor breathing continuously and more reliably. This would enable doctors to see trends that might not be apparent from manual observations and make more informed decisions about patient care.

The prototype paper sensors being developed by Spyras will provide continuous monitoring of respiratory rate, inhalation and exhalation periods and depth of breathing. Machine learning will help predict when a patient is beginning to deteriorate and alert clinicians early.

RESTORING ANCIENT TEXTS



A broken tablet with Greek inscription dating from the fifth century BC © SA3.0 Wikimedia

Researchers at DeepMind and the University of Oxford's Faculty of Classics have developed 'Pythia', a set of algorithms to restore text missing from ancient documents and tablets.

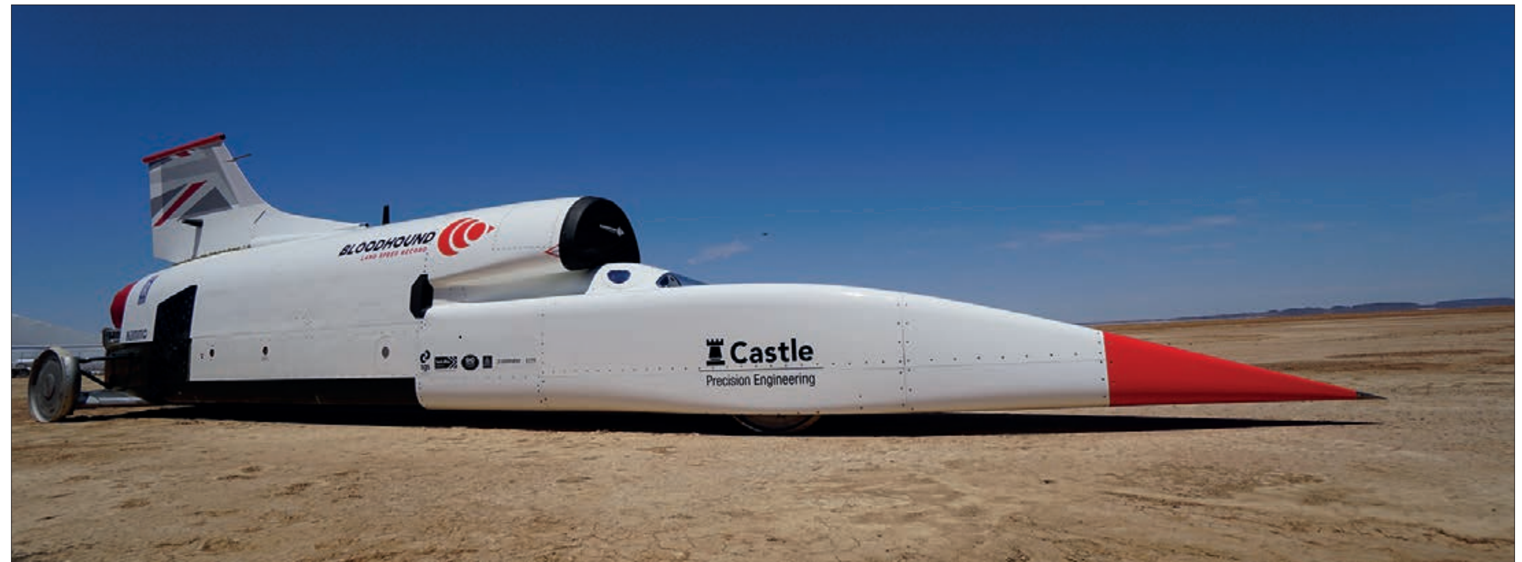
It's sometimes difficult for historians to read ancient tablets or manuscripts when entire sections of symbols have been wiped away. If a few characters have been lost, then reasonable guesses can be made, but when whole words or sets of words have gone then identifying the meaning of texts can be problematic.

Pythia consists of neural networks using sets of algorithms that have been trained to recognise patterns of ancient Greek inscriptions.

To train Pythia, the world's largest digital body of 35,000 ancient Greek inscriptions was converted to machine-actionable text. Pythia takes a sequence of damaged text as input and then generates 20 hypotheses, or character sequences, for researchers to compare and choose the one they think is the most appropriate. It does this in seconds, whereas human experts would take about two hours to decipher 50 inscriptions.

The system has a 30% error rate compared human experts' 57%. Pythia's ability to use contextual clues to make predictions makes it a useful tool for historians working on damaged Greek texts. An online version has now been open-sourced, which its developers hope will aid and inspire future research in the area.

BLOODHOUND SUPERSONIC CAR REACHES 1,000 KPH



The Bloodhound car reached its highest speed in the Kalahari Desert © Elliot Davies

In November, the Bloodhound supersonic car passed the 1,000 kilometres per hour landmark as it reached speeds of 1,010 kph (628 mph) in the South African desert, becoming one of the top 10 fastest cars in the world.

The car passed the 5-mile mark in just 50 seconds, as it prepared for its land speed record attempt in 2020, where it seeks to beat the 763.035 mph record. In Kalahari, the car reached the speed before twin parachutes were released to slow the car down. Slowing down the car is one of the key challenges – engineers and the driver need to know that the car can slow down and stop safely before they can increase the speed. It was the first time the car has been seen with its precision-machined solid aluminium wheels, made specially to withstand the stresses of traveling at supersonic speeds.

The Bloodhound team's primary objective is to engage and inspire people of all ages through the most extreme application of science, technology, engineering and maths.

BIONIC HAND 3D-PRINTED IN 10 HOURS

Engineers at WMG and the University of Warwick have 3D-printed a made-to-measure bionic hand in 10 hours.

The device incorporates muscle sensors to control an articulated thumb, enabling it to function similarly to a human hand. They have embedded the electrical circuitry linking the motion-controlling muscle sensors with the motors and battery into the structure of the bionic hand to provide a durable prosthetic.

Engineers have tested the durability of the printed electrical circuitry to understand how well it will endure the bending and flexing that it might experience in use.

They have also developed a website so that people can interact with the manufacturers to order a 3D-printed hand, allowing them to insert the measurements of their arm, and select what colour they want their hand to be, providing them with a tailored and personalised product.

The IMPACT project, led by Iterate Design and Innovation Ltd, in collaboration with WMG, University of Warwick, C Enterprise (UK) Ltd and Printed Electronics Ltd, was made possible thanks to a grant of nearly £900,000 from Innovate UK, with the aim of developing a 3D printing technology with the ability to print plastic products with integrated electrical circuitry, a capability that they have demonstrated in the bionic hand.

SOLVING LEAVES ON THE LINE

The use of dry ice would counter capacity issues on trains as large tanks of water would not be needed for cleaning
© University of Sheffield

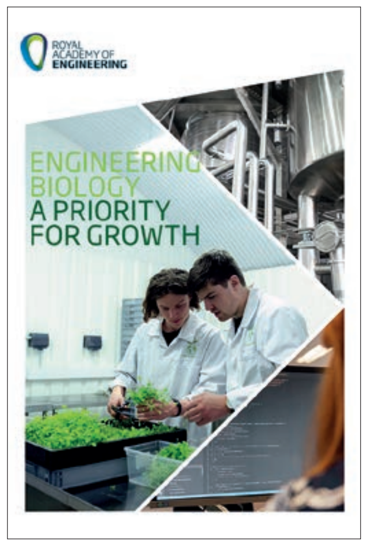
Professor Roger Lewis, a Royal Academy of Engineering Research Chair from the University of Sheffield's Department of Mechanical Engineering, is working with IceTech Technologies and Arriva Rail North to counter the effects of leaves on the line by using dry ice.

An estimated 50 million leaves fall onto the tracks of UK railway lines every autumn. As the leaves fall onto the rails, they are compacted under the weight of trains to form a slippery layer causing wheels to lose their grip. These issues are estimated to cost the railway industry around £345 million per year to address, as well as causing delays and cancellations.

The current solution to combat the low adhesion of wheels on rails is to apply sand direct from the train. This is done automatically when the train driver selects 'emergency braking' or when adhesion loss is experienced. This sanding process can cause damage to wheels and rails as well as leaving residue on the tracks.

The new method uses dry ice pellets to blast the rail head in a stream of supersonic air that freezes the leaves and makes them brittle. The pellets then turn back into gas, increase in volume and blow the leaves off the line. Trials were carried out on passenger services in October and November this year and could be rolled out across the wider rail industry in 2020.

ENGINEERING BIOLOGY



In November 2019, the Royal Academy of Engineering published *Engineering biology: A priority for growth*. The report highlights the UK's world-leading research in the field and its potential.

Its recommendations include calls on the business sector and others to adopt emerging technologies and accelerate commercialisation. Engineering biology applies engineering principles to design biological systems, with potential ground-breaking applications across a range of sectors: food, chemicals, materials, water, energy, health and environmental protection.

The innovations range from clothes made from spider silk, to meat alternatives and microbes used to manufacture fuels. Such techniques could disrupt existing industries with faster, greener and cheaper products and processes.

There are already more than 1,800 UK businesses undertaking industrial biotechnology-related activity. These employ over 14,000 people, generating £3.7 billion in revenue.

The report found a consensus of practitioners that recommend help to translate innovation into commercialisation.

The report recommends building better connections between well-established bio-technology companies and synthetic biology startups and spin-outs to scale and adopt emerging technologies to ensure that UK companies are international leaders in engineering biology.

Download the report at **www.raeng.org.uk/engineering-biology**

GET INVOLVED IN ENGINEERING

STEM BYTES FESTIVALS

National Museum of Computing

The National Museum of Computing holds STEM Bytes for creative computing fun. From Minecraft to Lego and Raspberry Pi to BBC micro:bits, there is plenty to do to unlock imaginations, inspire and entertain. Educational fun for all the family, providing byte-sized tasters of coding, robotics, augmented reality and virtual reality.

www.tnmoc.org/bytes

RIVERSIDE MUSEUM GLASGOW

NOW – 31 JANUARY 2020

Driving Force – Dorothée Pullinger and the Galloway Car exhibition showcases the story of Scotland's first woman car manufacturer. In 1922, Dorothée Pullinger was a pioneering engineer and an early member of the Womens' Engineering Society.

https://bit.ly/33sJkpw

THE NATIONAL SCIENCE AND MEDIA MUSEUM BRADFORD

Wonderlab

Get hands-on with interactive exhibits, including an anti-gravity mirror, echo tube and the light lab.

www.scienceandmediamuseum.org.uk/wonderlab

NOTTINGHAM FESTIVAL OF SCIENCE AND CURIOSITY

12 TO 19 FEBRUARY 2020

A week-long festival that takes science, technology, engineering and maths out of the lab and into our everyday lives.

http://nottsfosac.co.uk

CAMBRIDGE SCIENCE FESTIVAL

9 TO 22 MARCH 2020

A two-week celebration of science and engineering through talks, interactive activities, films and workshops.

www.sciencefestival.cam.ac.uk

THE BIG BANG FAIR

11 TO 14 MARCH 2020

The annual Big Bang fair in Birmingham is the UK's largest celebration of STEM for young people. Visitors to the fair can get hands-on at a range of workshops and exhibits, or take part in STEM shows.

www.thebigbangfair.co.uk

IN BRIEF EXTRA

88 PIANISTS WORLD RECORD

Students prepare to take a bow in front of the grand piano and 88 connected mechanical 'fingers'

On 21 August, 88 schoolchildren from across the UK broke the world record for the highest number of people playing the same piano simultaneously. A previous record had been set last year with 21 school pupils in Holland gathered around, below and above a single piano.

The UK record attempt was the culmination of a two-year project initiated by Professor Julian Allwood FREng, Professor of Engineering and the Environment at the University of Cambridge. Rather than have lots of people each touching the keys, Allwood decided to turn the feat into an engineering exercise for primary school students and university researchers. He gathered a team of 100 young professional musicians and engineers who worked with 35 schools to stimulate pupils to think about and practice engineering principles. The end result was a complex mechanism that succeeded in playing all 88 notes on a concert keyboard at the International Convention Centre in Birmingham in front of an audience of 2,000.

The original idea was built around the wish to celebrate the 500th anniversary of the death of Leonardo da Vinci. While Leonardo da Vinci is most famous as a painter, he also had a keen interest in maths, engineering and invention. Professor Allwood posed the question "Has the smart phone killed invention?" and wanted a project that would fuse science and art to test this question. Engineering researchers worked with Key Stage 2 pupils to beat the piano playing record. "The most efficient way to play a piano key with 88 people would be to position them seven metres away with a light stiff wire pulling a simply-pivoted lever at the keyboard." Professor Allwood says, "But it's better, far better, to play the key with an ultra-awesome toothbrush, a banana gun or a flying rabbit projected by a catapult which is what we ended up with!"

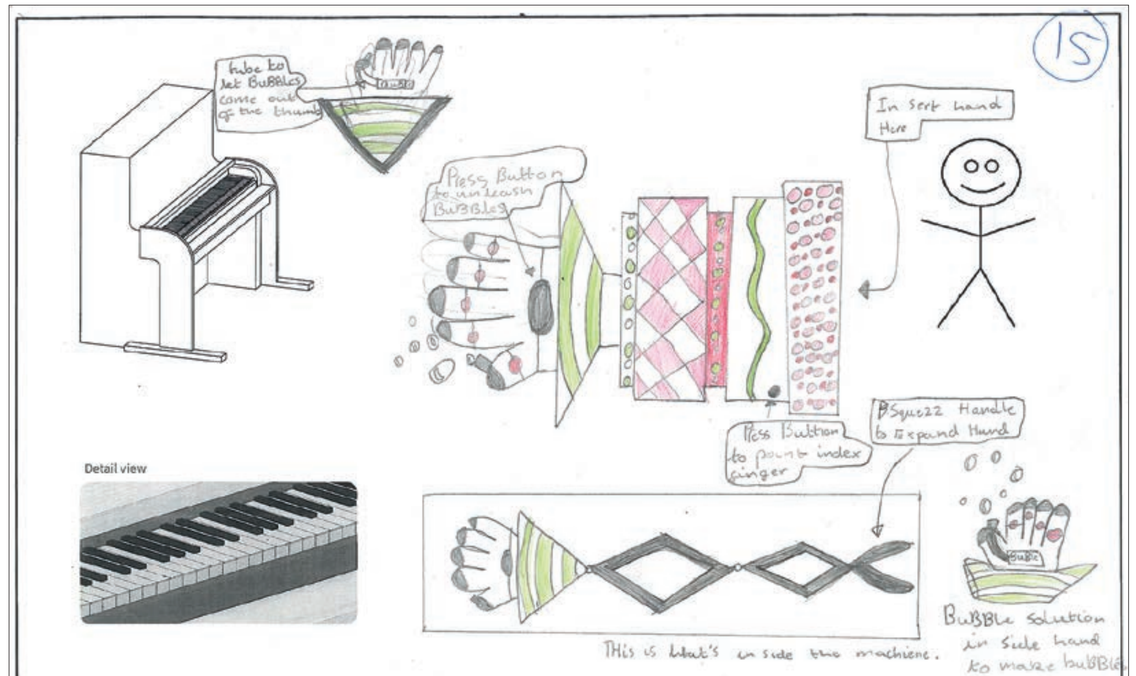
Teams of two engineers and a musician from the Royal Birmingham Conservatoire at Birmingham City University visited 35 schools three times over a year building up to the performance. For the first visit, children worked in groups to build a mechanism to play a chime bar remotely from a kit of parts, and then to work as a class to make a simple piece of music with their mechanisms. They were then given a piece of A3 paper, with a picture of a piano on one side and a stick-player at the other, and asked if they could invent a way to play the piano that no one had ever thought of before.

Brockwell Junior School using the kit of parts. The school's design of interconnected cogs was chosen to play the 26th key of the piano

"With that simple request", says Allwood: "Heaven's gates opened. Unconstrained by any sense that there might be a 'right answer' and with a cavalier disregard for the principles taught in first year undergraduate courses in engineering, the children responded with a freedom we couldn't possibly have anticipated or recreated ourselves. By Christmas we had received 2,500 original solutions to our challenge, with extraordinary ideas both for the mechanisms themselves and for their appearance."

The Stretcherlator designed by Abbey Junior School involves a decorated hand, mounted on jack scissors operated by a set of connected levers. This was turned into the device to hit the 15th key.

A panel selected 88 designs and two more visits were made to each school. Converting the pupils' designs into reliably-working mechanisms involved designers of all levels of experience solving a variety of engineering challenges. How much lateral movement would be needed in a Rainbow-unicorn-cat-spaghetti-meatball-see-saw? What shape should the flowers be to ensure that, as the carriages of a flower-train collide with a short lever-arm, the note plays reliably? How stiff and taut should the string connecting the giant door to the interface be?



The Stretcherlator designed by Niamh at Abbey Junior School. The students built a giant hand that extended using a pantograph mechanism, which works like an accordion. This was turned into the device to hit the 15th key

Enabling the assembly of the mechanisms depended on the inspiration of chief engineer, Dr Chris Cleaver in Cambridge, who created an architecture for the whole project with two critical designs. Firstly, he designed an interface at the piano keyboard, rather like a mechanical typewriter, to allow the children's mechanisms to pull, push or impact one end of a lever whose other end (protected with the tip of a snooker cue) would play the piano key. Secondly, he designed a floor plan to show where each mechanism could attach to the floor: even at a seven-metre radius, each mechanism could only be 25 centimetres wide if the players stood within a semi-circle, so lateral stability was critical.

Researchers in manufacturing technology at the Universities of Cambridge, Sheffield, Liverpool, Nottingham, Bath and the Advanced Manufacturing Research Centre in Sheffield helped hone the individual designs. In the weeks before the concert the full set of mechanisms were set up and tested in a large lab at Cambridge.

Two removal vans brought the full assembly to the International Convention Centre in Birmingham, where a team of 30 engineers erected it. After a rehearsal, the construction was fine-tuned. The next day, the International Academy of Production Engineering watched the demonstration of creativity in engineering and music. Fifteen minutes after, Julian Lloyd Webber, Principal of the Royal Birmingham Conservatoire, confirmed to the audience that all 88 notes had been played, establishing a new world record. A media storm followed with appearances on BBC's One Show and 4.5 million hits on the Chinese blogging site Weibo.

A film of the performance and an interactive keyboard showing the story behind every note is online at ***www.88pianists.com***

HOW I GOT HERE

HOW I GOT HERE

Q&A

MAMTA SINGHAL
DESIGN ENGINEER AND CAMPAIGNER FOR DIVERSITY IN ENGINEERING

Mamta Singhal is a Commercialisation Manager for Coca-Cola European Partners, GB Supply Chain. Before this, she worked for two large toy manufacturers as a design engineer with Hasbro and as a project quality engineer for Mattel.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

When I was seven years old, I often tested how things worked. So, I would take apart watches, pens, phones and hairdryers to see what was happening inside! My father is a physicist and he encouraged me and my sister to have open minds in regards to learning and following our passions.

By the age of 10, I found myself wanting to do maths for fun and gravitated towards logic puzzles and STEM buildings blocks. When I was 13, I remember my dad taking me to the James Watt School of Engineering at the University of Glasgow and I was amazed by the place. My father has been a STEM spokesperson in Scotland for 50 years and I remember watching him speak publicly and finding it fascinating.

HOW DID YOU GET TO WHERE YOU ARE NOW?

I studied an affiliated degree course in product design engineering at the James Watt School of Engineering at the University of Glasgow and the Glasgow School of Art. Following that, in 2002, I took a master's at Strathclyde University's Design, Manufacturing and Engineering Management department. I then worked around the world for four years as a design engineer for Hasbro developing various engineering skills such as prototyping and tooling processes.

I returned to Scotland to study for an MBA at Strathclyde Business School. The two years spent there helped me learn about the areas of new product development and supply chains. I then worked in the food industry, first with Mars before joining Coca-Cola European Partners as a commercialisation manager.

WHAT HAVE BEEN YOUR BIGGEST ACHIEVEMENTS TO DATE?

I was pleased to gain my MBA with over 80% in all subject areas studied and then, in that same year, 2007, I won the Young Women Award from the Women's Engineering Society. I recently gained my CEng accreditation and so am now a chartered engineer. Each of these have been meaningful for different reasons but together they have helped me establish myself in the world of engineering, business and society.

I have continued to work with the Institution of Engineering and Technology (IET) and in October 2019 I became a member of the IET Council and am very excited about what opportunities that will bring.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

Well, no day is ever the same. One day it will be dealing with calls and emails with perhaps an international video conference. Other times I may need to review prototypes, make a factory visit, or do project planning; it varies.

I work on manufacturing designs focusing on engineering quality, compliance, sustainability, packaging and streamlining supply chains. I use technical applications to make consumer items, from working out the size of monopoly pieces to improving the flow-wrapping for chocolate bars.

One of my favourite jobs was working as a Project Quality Engineer at Mattel. This involved helping ensure that the company manufactured goods that were safe and complied with regulations in the toy sector. I spent a lot of time measuring, checking and rethinking engineered pieces so that the amount of materials could be reduced and the items could be made safely. I sometimes helped make a toy more enjoyable and playful to use.

Hasbro was where I started my career in toys and I modelled game pieces using computer-aided-design and then produced 3D scaled mock ups of them. I would then 'debug' these first prototypes, ensuring that errors were spotted before going into full production. It felt a little like looking into the future, working on games and toys that would one day be wrapped up and played with.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER

I love looking at materials and objects and working out how they are made and constructed.

The good thing about being an engineer is that I get to meet a range of people, all ages and academic backgrounds with differing views on subjects, which in turn makes for a collaborative and dynamic spirit at work.

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

A degree in engineering opens doors. Our global future requires us to be sustainable, to tackle climate issues, to build smart buildings, to develop new packaging, all of which requires smart engineers. For me, studying engineering was the best thing I ever did.

Mamta Singhal meeting students who won the chance to meet engineering role models at the House of Commons in 2018 by entering a competition organised by LEGO Education and the IET © IET

WHAT'S NEXT FOR YOU?

I am aiming for my Fellowship with the IET, a more senior position in industry and an honorary professorship/lectureship. Inspiring future engineers is a definite target.

QUICK-FIRE FACTS

Age: **Late 30s**

Qualifications: **BEng, MSc, MBA, CEng, MIET, MWES.**

Biggest engineering inspiration: **My dad.**

Most-used technology: **My smartphone.**

Three words that describe you: **Collaborative, entrepreneurial and STEM-lover.**

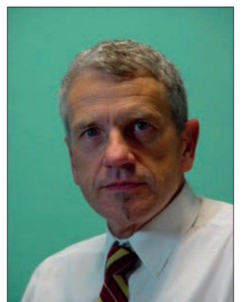
OPINION

OPINION

NEW TECH CREATES 999 OPPORTUNITIES

The immediacy of a personal response to a call for help is regarded as being invaluable, but technology is starting to emerge that can pre-empt a call having to be made in the first instance

In the UK keying 999 or 112 into a phone results in a truly integrated national emergency response.


Dr Nigel P Brown

Ask 999 callers what they expect from an emergency service and you receive a coherent reply: a human voice that provides a fast response that resolves their immediate personal crisis. If you ask emergency responders what they want to deliver they are equally clear – reducing suffering and saving life. However, the response is largely predicated on a verbal conversation with the caller that has barely changed in the 80 years since the world's first service was pioneered by the police in London. Callers may be unable to adequately, or quickly, describe where responders can locate them let alone provide accurate information to assist in mobilising an appropriate response.

In caller's minds there is little agreement of what an emergency constitutes: either the nature of the incident, its magnitude or severity. Crises can range from the need to extinguish a 'fire' – which can ambiguously range from a smouldering rubbish bin to an entire building engulfed in flames – to a life-threatening medical emergency where a rapid response can be the difference between death and a good chance of recovery. Mobilising scarce resources is a challenge: an ambulance with two paramedics might be dispatched and it turns out that they only dispense aspirin, or a fire engine arriving on the scene may immediately request support owing to the scale of the incident. Accurate information plays an important role in delivering an efficient and effective service.

When a 999/112 call is answered, much technical activity has gone on behind the scenes. If the call is made from a GPS enabled device, this functionality is automatically activated and the location of the phone made available to responders. Yet, matching the response to the caller's crisis remains largely manual, and effective triaging can take even skilled operators vital minutes. It is for this reason emerging technology such as artificial intelligence (AI) is starting to be used to analyse voice calls. With time of the essence it is also vital that skilled operators can draw upon imagery that might help clarify a call for assistance, but it is also important that they are not overwhelmed by having content involuntarily 'pushed' to them. Imagery could well be useful even after resource has been dispatched to upgrade or downgrade the response.

Smartphones now have capabilities far beyond just making a call for help. Those making an emergency call on their smartphone actually have access to seemingly boundless information through being connected to the Internet, the power of an awesome computing resource, and upwards of 20 measurements from sensors exhibiting increasing reliability and precision. Sensing can be extended to the actual owner by a smart watch.

Linked devices and phones are already aware of their immediate situation and are increasingly capable of setting this in a temporal context, possibly through several years' association with the owner. Context can also involve spatial position: whether the phone is likely to be with its owner and whether that person is actively running or stationary and horizontal. Other sensors can provide what medics call 'vital signs' such as heart rate, breathing pattern, skin moisture level and temperature. Access to such information could help triage a personal crisis without the need for owner intervention, helping to better match any response by the emergency services closer to the actual need, thereby delivering a more efficient and effective all-round service.

Embracing these innovations, a future service can now be imagined beyond conventional boundaries.

Currently the 999/112 service is largely response-focused despite non-emergency numbers such as 101 and 111 providing a preventative dimension. The immediacy of a personal response to a call for help is regarded as being invaluable, but technology is starting to emerge that can preempt a call having to be made in the first instance. Sensors associated with smartphones are already providing early notification that a medical emergency might be emerging, enabling early intervention. This capability is enabled by personal apps that are increasingly starting to address specific issues. While the app landscape is currently fragmented, the underlying capabilities tend to empower rather than instruct.

Any change to an established service like 999/112 will need to be considered – embracing change while ensuring continuity rather than disruption to the service. Apps for smartphones will continue to emerge, most likely at an ever-increasing rate. Many have been developed with good intentions but their developers often forget about the downsides that they create such as false alarms. In Britain, APCO, an emergency services trade association, runs a scheme to certify apps to ensure that when they are released they behave as intended. BT call centres that answer around 30 million 999/112 calls a year with the reassuring phrase "Emergency, which service?" are about to undergo change as the switched telephony infrastructure in the UK is migrated to IP – or Internet protocol – a true data thoroughbred. Changing the underlying technical platform will provide opportunities to integrate new services such as real-time text or imagery with greater effect.

There is a lot of activity with a common theme of harm reduction, largely characterised as being responsive to those in need of assistance. The future might be very different, involving emergency communications from the authorities – a sort of 'reverse-999' – and capabilities that empower people to make informed life-saving decisions not only for themselves but those around them thereby nuancing the personal emergency from passive to participatory. Making sense of the information available in our increasingly information-rich society to enable people to make personal decisions around harm reduction and provide emergency services with greater situational awareness to better match a response, is both an exciting and complex challenge.

Dr Nigel P Brown
Cabinet Office
Lead for Resilient ICT Strategy

BIOGRAPHY

Dr Nigel P Brown works for the UK government Cabinet Office in the Civil Contingencies Secretariat. The Secretariat works with government departments, the devolved administrations and key stakeholders to enhance the UK's ability to prepare for, respond to and recover from major incidents. Nigel focuses on security and resilience strategy for the information and communications technologies and energy sectors. He is a chartered chemical engineer and holds BSc, PhD and MBA degrees from Imperial College London.

COMPLETING THE SAGRADA FAMÍLIA


The Nativity Façade of La Sagrada Família, Barcelona. Construction work began on the basilica in 1882 and has been ongoing since © Fundació Junta Constructora del Temple de la Sagrada Família

Antoni Gaudí's masterpiece, the Sagrada Família church in Barcelona, has been under construction for nearly 140 years, but only 60% of the structure had been built by 2014. Now, using modern engineering and construction techniques – including innovative prefabricated prestressed stone panels – the remaining 40% is due to be completed by 2026, the centenary of Gaudí's death. Tristram Carfrae RDI FREng, deputy chairman of Arup, explained to Hugh Ferguson how this is being achieved without compromising Gaudí's vision or quality standards.

Arup was called in to collaborate with the Sagrada Família Foundation and its well-established team of in-house architects and builders in 2014, initially with one particular challenge: one of the 18 towers – the Mary Tower over the crypt – was going to weigh too much for the foundations installed in 1877, and some fresh ideas were needed. How could a tower be designed and built that would work both structurally and visually, while following the guidelines that Gaudí had set, and maintaining the highest quality? An earlier idea had been to erect an interior steel structure on which stonework could be hung, but this was seen as inappropriate.

Meanwhile other factors were at work. The trickle of donations to fund construction had turned into a torrent, as Barcelona's booming tourist industry brought more paying visitors, particularly after the completion of the nave and consecration of the church by Pope Benedict in 2010 – there are currently some four million visitors per year. A major constraint on the speed of construction had been removed, and the bold decision had been taken to complete the structure (but not necessarily the decoration) by 2026. This required a tenfold increase in the speed of construction compared to the previous 130 years.

Another element to consider was that traditionally all construction work for the church had been done on the site, which was becoming cramped as the building expanded. It was also becoming unmanageable, as the pace of construction (and hence the workload) increased, and the church was still having to remain open for its many visitors. The case for off-site fabrication was strong.

A prototype column, showing the stainless steel rods threaded through the drilled masonry, and the anchorage plates for prestressing © Arup

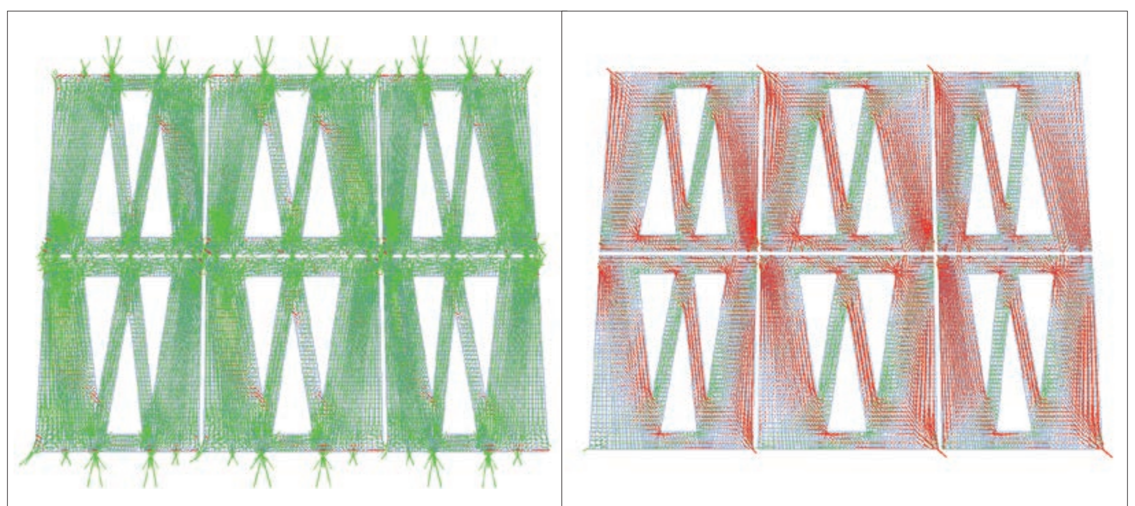
3D MODELLING

The first action was to determine the shape of the tower. No models or drawings of the Mary Tower survived, so a design had to be recreated from fragmentary archival evidence and by extrapolating from Gaudí's use of geometry (see box) in his model for the sacristy. A series of hyperbolic paraboloids were rotated about a central axis and intersected. This was then modelled in Rhino 3D software and elongated to create a tower with a scalloped multi-sided shape in plan, with many small triangular windows, shaped as hyperboloids.

Next a structural form was needed. Various ideas were conceived, modelled in Rhino and then tested by finite element analysis to reveal the stress levels in each element under different loading conditions. Earthquake loading was important, but in most cases the critical condition was under extreme wind loading. Each idea was tested at various levels of computer analysis, starting with the 'quick and dirty' and moving swiftly to the highly detailed.

As a start, Arup modelled what would happen if the tower was built in traditional stone masonry (thin enough to be within the weight that could be carried by the foundations). Under normal loading the tower behaved reasonably well but under extreme wind loads all parts of the masonry facing the wind went into tension. As traditional masonry is very strong in compression but very weak in tension this approach would not work.

After further modelling a potential solution was proposed. Instead of using traditional construction, what if the masonry was pre-formed in larger panels and prestressed using tensioned steel rods before erection? In this way, the masonry could be pre-compressed so that it would be much less likely to go into tension under wind loading. Panels around 4 metres high by 3 metres wide, 14 to a ring of the Mary Tower and weighing around 5 tonnes each would suit the geometry and be reasonably easy to create and erect. The panels could then be simply bolted together, with shear connectors on the horizontal joints.



Stress analysis of a section of the Mary Tower under extreme wind loading, showing large areas in tension (red) using traditional masonry), compared with almost all in compression (green) with prestressed masonry panels © Arup

Finite element analyses demonstrated that this strategy could work. Under extreme wind loading, almost all elements of the panels remained in compression, though there were some elements that could move into tension (red, in the diagram), which could then lead to a crack forming in the masonry. The question then was whether the crack would open up with serious consequences or whether the loads would redistribute safely in the remaining structure: a simple re-run of the analysis removing the element in tension, confirmed the latter.

The prestressed masonry panels had the additional advantages that they retained the use of Gaudí's preferred sandstone as the primary structural material, they were ideally suited to off-site construction, and they achieved the necessary weight reduction: the stone in the panels is just 300 millimetres thick, compared with around 1.2 metres for traditional masonry, and resulted in a structure just light enough for the foundations.

Once the overall form was determined, the team modelled every component of each panel to a construction level of detail, including nuts, bar threads, couplers, fillets and chamfers. In this they were assisted by full-scale mock-ups produced by the Foundation, to check appearance, and for 'buildability'. Every detail was carefully planned, and a kit of parts assembled including the stainless steel rods and bolts for the prestressing. Careful design of connections combined with precise manufacture ensured that the panels when craned into position could fit together like Lego blocks, with no on-site adjustment.

OFF-SITE PREPARATIONS

Meanwhile a suitable fabrication site was found north of Barcelona, some 90 minutes from the church. Here the digital model was used to

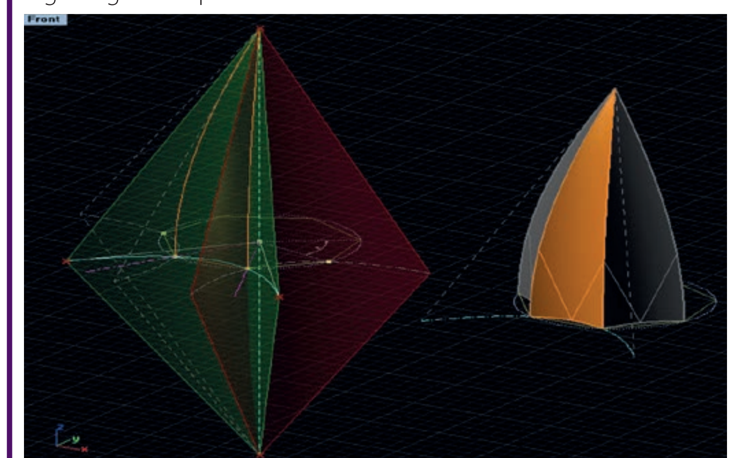
ANTONI GAUDÍ – ARCHITECT AND ENGINEER

Antoni Gaudí was in his early thirties when he took over as architect for the Sagrada Família, before his modernist buildings in Barcelona had established his reputation. His appointment followed the resignation in 1883 of his predecessor, with the stone crypt of a neo-Gothic church already nearly complete.

Gaudí spent the next 43 years developing his own distinctive design for a far larger and different structure, in his later years working exclusively and obsessively on the church, driven by his profound Catholic faith. He never expected the church to be completed in his lifetime, and as he once famously observed: "My client is not in a hurry". Besides, construction was funded by private donations and could proceed no faster than the flow of money.

But he left plenty of clues as to how it should be finished. He completed the crypt, the façade of the apse and just one of the planned 18 towers, plus much of the Nativity entrance – which served as examples. He also left extensive drawings and plaster models. An explosion during the Spanish Civil War destroyed or extensively damaged many of the drawings and models, though much has been recovered by painstaking restoration. Where models exist, the current design team follow them exactly. Where only drawings or fragments of model remain, the team uses a degree of interpretation, complicated by the changes in Gaudí's thinking (and drawings) during his lifetime. Where there is no evidence, they can freely interpret his intentions.

In his later years, Gaudí became fascinated with geometry, and he designed much of the masonry structure and the whole of the interior of the church and its ornate decoration using just two key figures: the hyperboloid, a little like a three-dimensional hour-glass, and the hyperbolic paraboloid, the saddle-shape of a Pringles potato chip. Complex shapes curved in three dimensions can be created from either figure, but both have one interesting feature in common: they have ruled surfaces, which means it is possible to draw a straight line along the surface through any point. Though Gaudí cannot have anticipated it, this feature provides an extraordinary advantage to 21st-century engineers trying to replicate and construct his designs: any of his shapes can be modelled in 3D software, and then cut using robot operated, computer-controlled diamond band-saws or lasers, to high degrees of precision.



Resolving the geometry. The shape of the Sacristy, created by rotating a series of hyperbolic paraboloids about a central axis © Fundació Junta Constructora del Temple de la Sagrada Família

Lifting and placing a 25-tonne prestressed masonry panel for the Mary Tower high above the Barcelona skyline © Fundació Junta Constructora del Temple de la Sagrada Família

automatically cut the stone, with its angled jointed surfaces finished to within 1 millimetre by computer-controlled cutting. A more traditional method was used to match the rest of the church with the outer finish of naturally broken sandstone: the edges were hit very hard with a sledgehammer.

Then the individual stone blocks were fabricated into a panel using laser-cut plywood templates, and prestressed with machined duplex stainless steel bars, inserted through holes predrilled through the masonry. Finally the holes were grouted, to provide further long-term protection to the steel rods.

In this way a production line was formed. Each of the 14 panels in a ring was identical, so there was helpful repetition, but as the tower is tapering, each successive ring was smaller as the tower rose. It took a month to fabricate each ring, but then only a day to assemble it on site: the care taken in design and the accuracy of manufacture meant that the panels slotted together rapidly with a minimum of fuss, so minimising both the use of limited crane access at the church and disturbance to church activities and its visitors.

The principle of prestressing masonry panels and the off-site production method have been adopted for construction of the remaining towers, in particular, the tallest of all, the mighty Jesus Tower that sits above the crossing of the nave. Before Arup's arrival, the plan had been to build the tower in reinforced concrete and clad it in stone. But experience with the Mary Tower demonstrated that prestressed masonry panels would not only be more appropriate, but also easier and faster to build.

COMPLETING THE TOWERS

Construction started in July 2019 and the process has been identical to the Mary Tower except on a larger scale: the masonry thickness is 450 millimetres instead of 300 millimetres, there are 12 panels per ring instead of eight and each panel weighs 25 tonnes instead of 5 tonnes. When the Jesus Tower is 'topped off' with its five-armed cross, the Sagrada Família will be (at 172.5 metres) the world's tallest church and Barcelona's tallest building.

Inside the Jesus Tower a lift and staircase will carry visitors up into the cross. The spiral stone staircase will be cantilevered from the inside of the stone-panel wall, following a long tradition in masonry architecture. In this case, there is the added complication that the staircase has to span some of the openings in the tower: the solution, again, is to post-tension the stone to allow the staircase to bridge the gaps. The lift shaft will then be assembled up the middle of the tower.

Tristram Carfrae is well used to working closely with architects and builders worldwide, but never before has he experienced such close collaboration – due in part to the long-established in-house architect/builder team and in part to the simple, shared objective: to build the best church in the world. "It just makes me inordinately happy, and fulfilled, and pleased that I became a structural engineer to get to work on things like this."

For more information about the project see **www.arup.com/sagrada-familia**

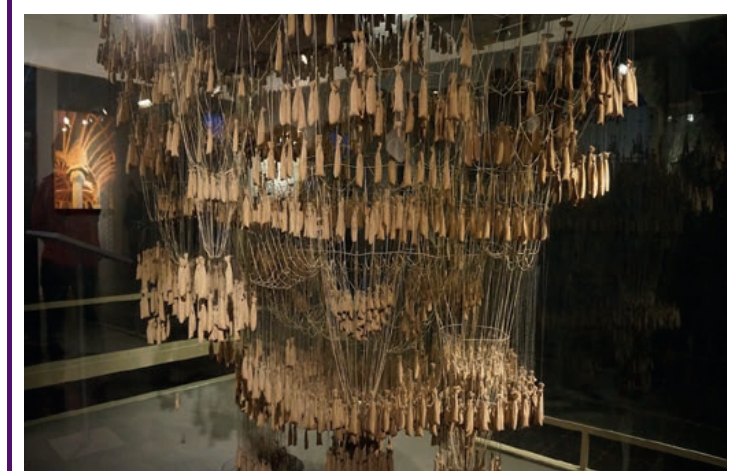
CATENARY CURVES

One of Gaudí's objectives was to avoid a characteristic feature of Gothic churches – the flying buttress – that carries to the ground the lateral forces from the vaulted ceiling. These he believed to be unsightly 'props', not integral to the church. More importantly, they block the light entering the building, and Gaudí was determined to have the interior of his church flooded with natural daylight.

For a solution he turned to the catenary – the natural shape found by a chain hanging loosely between two supports. Invert the catenary, and you have an arch that will convey its weight to the ground with no transverse forces. If you then 'distort' the catenary by adding weights to represent the additional masonry that the arch will have to support, you create a shape that requires no buttresses.

Gaudí produced elaborate models, with bags containing lead shot attached to his chains, in order to discover the perfect shape. The result can be seen in the nave of the Sagrada Família, which was eventually completed and opened in 2010: the stone columns, viewed in cross-section looking down the nave, are Gaudí's catenaries, with no verticals. The exceptions are the four vertical columns of the crossing, which will support a massive tower above.

Gaudí compromised in that his catenaries were only used in two dimensions: viewed in long-section, the columns are all completely regular and conventionally vertical.



An upside-down force model of the Colònia Güell in the Sagrada Família Museum. Gaudí would hang strings and weights then use the resulting 'catenary curve' to model columns and arches. He would render the model upright by placing a mirror underneath or by taking a photograph © Fundació Junta Constructora del Temple de la Sagrada Família

When the Jesus Tower is 'topped off' with its five-armed cross, the Sagrada Família will be (at 172.5 metres) the world's tallest church and Barcelona's tallest building

BIOGRAPHY

Tristram Carfrae RDI FREng is a structural engineer and Deputy Chairman of Arup. He has been responsible for the design and structure of many award-winning buildings during his 37 years with the firm, both in Australia and the UK. In 2014 he was awarded the prestigious Gold Medal award by the Institution of Structural Engineers and in 2018 he became the fourth Briton to receive the IABSE's International Award of Merit in Structural Engineering.

Livers placed within the metra continue functioning throughout the preservation period and key parameters are continuously monitored. The metra graphical user interface enables the transplant surgeon to view variations in markers of haemodynamic, synthetic and metabolic performance throughout this period © OrganOx

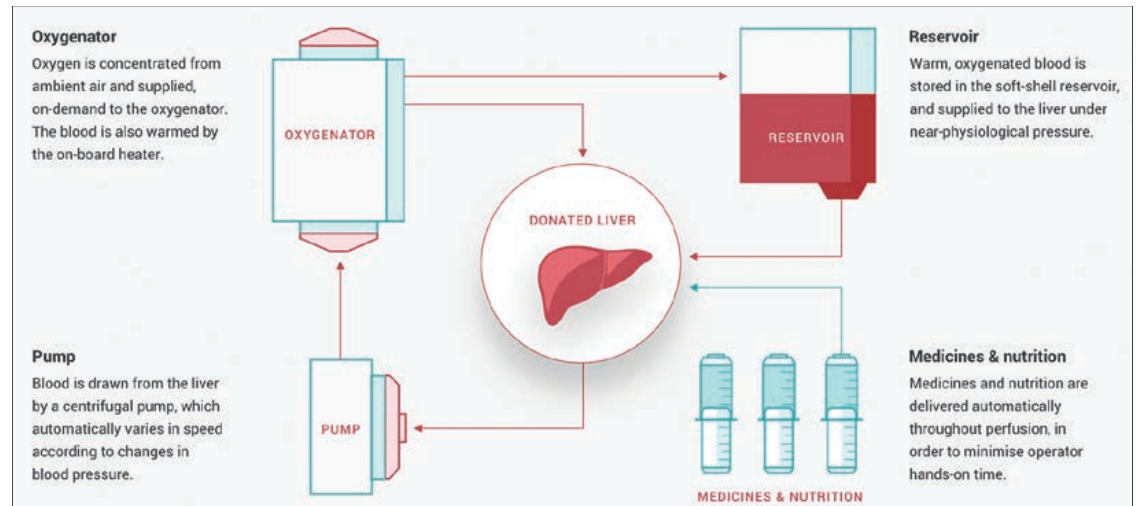
KEEPING TRANSPLANT LIVERS ALIVE

The OrganOx metra® is the world's first fully automated system for keeping a human donor liver functioning for up to 24 hours outside the body. The invention breaks with 40 years of traditional organ preservation in ice, doubling the length of time that donor organs can be preserved before transplantation. Geoff Watts talked to members of the OrganOx team to find out how this breakthrough came about.

Until recently, doctors who had identified and removed a potentially suitable liver for organ donation would cool it to 40°C, place it in an ice box, and transport it as quickly as possible to one of the surgical centres where it could be used. This might take several hours – during which time it was hoped that the liver would lose as little as possible of its functional capacity.

Like surgeons before him, Peter Friend, Professor of Transplantation at the University of Oxford, reasoned that the chances of preserving a liver during its time outside the body might be enhanced if, instead of cooling the organ, it could be kept at body temperature in conditions as similar as possible to those it normally experienced. As well as keeping the temperature constant, a continuous blood supply could bring the liver oxygen and other nutrients.

This 'normothermic' strategy had in fact been tried a number of times in the past, but without success. By going back to basics, and learning more of the biology of the liver, Friend – working closely with colleague Professor Constantin Coussios FREng of the Oxford Institute of Biomedical Engineering – devised a successful method of achieving this goal. Coussios and Friend set up a company called OrganOx to develop a practicable machine for preserving isolated livers under physiological conditions. The OrganOx metra® is now on the market.



A flow schematic showing how the metra achieves machine perfusion for liver transplantation © OrganOx

COMPLEX BIOLOGY

In principle, the metra simply aims to replicate what goes on in the body – though 'simply' is a monumental understatement. A schematic flow chart of the machine's 'plumbing' – its various components and the tubing that carries blood between them – reveals little of its complexity. Running the metra requires three units of blood, a little over 1.5 litres. Playing the role of the heart is a pump that initially pushes the blood through an oxygenator. The liver, unlike most organs in the body, has two blood supplies, the hepatic artery and the portal vein. The metra mimics this arrangement. Some of the oxygenated blood is channelled directly to the isolated liver

One reason why previous attempts to mimic the natural perfusion of isolated livers have failed is that these organs, even when detached from the body's nervous system, retain the capacity to vary their resistance to blood flow going through them according to their need for oxygen or nutrients

though a tube that enters the stump of the hepatic artery. The rest is pumped into a reservoir where nutrients, including insulin and heparin, to prevent clotting, are added. Only then is this portion of the blood also channelled to the liver – in this case through the stump of the portal vein. Blood from both sources exits the liver via another vessel, the inferior vena cava, passes through a blood gas analyser, and re-enters the pump.

In engineering terms, you may think, a fairly straightforward set up. Coussios knows otherwise, remarking that "biology really teaches engineers a lesson in humility". You get a hint of this on learning that each metra comprises a staggering 40,000 components.

LIVER TRANSPLANTATION

A liver transplant becomes necessary when the recipient's own organ is diseased or damaged beyond repair. The main causes of severe liver damage include cirrhosis, hepatitis, various metabolic conditions and paracetamol poisoning.

In the UK, more than a thousand livers are transplanted each year. But this number does not meet the full extent of the need. The average waiting time for a liver transplant in the UK is more than 130 days for adults and more than 70 for children. Not surprisingly, some patients die while on the waiting list.

Many potential donor organs cannot be used because their condition is sub-optimal. Such livers do not tolerate conventional cold storage and, until now, there has been no reliable way to assess the viability of an organ preoperatively.

Preparing the OrganOx-preserved liver for connection © OrganOx

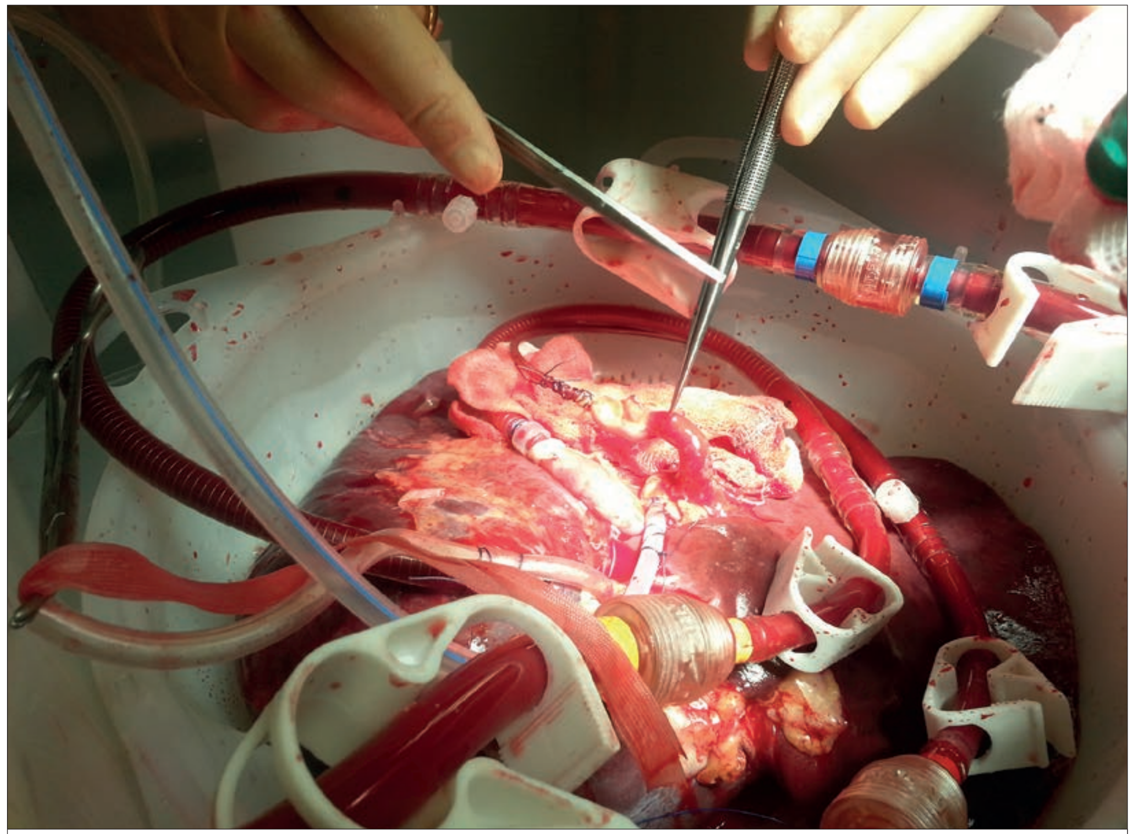
PREVIOUS FAILURES

One reason why previous attempts to mimic the natural perfusion of isolated livers have failed is that these organs, even when detached from the body's nervous system, retain the capacity to vary their resistance to blood flow going through them according to their need for oxygen or nutrients. These changes in resistance – and the consequential changes in the organs' demand for blood – can be rapid. To cope adequately with such fluctuations in an artificial system proved to be a thorny problem.

Most researchers have tried to maintain physiological arterial pressure at the inlet to the organ by modulating the flow rate of the pump, thereby artificially setting the flow rate through the organ. But this, while relatively straightforward to achieve, is not how the body itself operates. The metra is designed not to maintain a constant flow of blood, but a constant pressure difference across the organ, enabling the organ to 'choose' its own blood supply. This well-known biological phenomenon is termed autoregulation. Achieving it was complicated by the liver's exceptional plumbing: one outflow of blood, but two inflows. Imitating the natural physiology of the liver proved to be an engineering challenge that took years to overcome.

Control loops relying on sensors in a conventional engineering feedback system find it difficult, if not impossible to match the speed of natural biological control systems. In the first one to four hours following removal of a donated liver, changes within it are particularly rapid, and any physiologically abnormal perfusion can cause severe damage to the organ's vasculature.

One way that Friend and Coussios minimised the problem was to choose components for their system that had a degree of autoregulation. An example is the type of pump that propels the flow and volume of the metra and through the liver. In a roller pump of the kind used in most cardiopulmonary medical devices, the flow rate of the blood is determined by the roller's speed of rotation. The



A liver being perfused on the metra © OrganOx

metra uses a centrifugal pump in which the outflow is determined both by the rotational speed of the pump and by the downstream resistance. So if vessels in the liver undergo constriction, the outflow of the pump is instantly reduced even before its rotational speed has decreased. The organ is, in effect, controlling its own blood supply.

This, however, throws up another problem. Any change in the resistance of the organ that requires a change in pump speed will precipitate a need to alter the settings of the other controls in the system, in particular the valves that regulate the flow and volume of blood passing through the liver. In fact, there are no fewer than seven independent controllers within the metra dealing not only with pressures and flows, as measured by flow sensors located at critical points, but with several other variables such as temperature, blood gas levels and nutrition. The needs of the isolated liver with respect to each of these variables were originally unknown; they had to be established through experiments before engineering to replicate them could begin.

Designing a strategy for the machine's controllers was perhaps the greatest challenge of the whole project. As Coussios comments, working with a nonlinear system characterised by multiple inputs and outputs in which a change in one affects all the others is, to say the least, demanding.

MORE HURDLES OVERCOME

Also problematic, though for different reasons, was the supply of gas required by the metra's oxygenation unit. Standard gas cylinders are too heavy and cumbersome to create a portable machine that can support an organ for 24 hours. The metra utilises oxygen concentration technology in a novel device that produces the gas in the required amount from the atmosphere, only when it's needed. The oxygenator is also responsible for warming the blood to 37°C.

The body's vascular system has evolved to do minimum damage to the red blood cells swept along within it. These cells are susceptible to shear stress of the kind often created by artificial devices. To overcome this it was necessary to measure and then optimise the design of every bend and twist in the fluid path. It might be imagined that the greatest source of shear stress would be the pump. In fact, it turned out that the most damage was done by vortices that formed in the blood as it passed through the valves. These had to be specially redesigned to minimise the emergence of such vortices.

The system's blood reservoir takes the form of a soft flexible bag. Nutrients, such as heparin are introduced into the bag in predetermined quantities at a pre-set rate by means of a set of screw-driven syringes. From the reservoir, the blood flows into the liver via the second of its supply vessels, the portal vein. Although complicated in design and actions, the metra is surprisingly simple to use, and carries only 'play', 'stop' and 'eject' buttons: one of the reasons that it took so long to perfect. The machine

The metra can be loaded onto vehicles used by transplant teams. The protective hard covers for transport leave a space for the graphical user interface screen and the liver bowl to remain visible © OrganOx

is, as Coussios rather wickedly describes it, "virtually doctor proof".

A WORKING LIVER

The donor liver itself is supported on a silicone rubber sling inside an enclosed box. This arrangement allows any fluid secreted by the organ to be collected and returned to the reservoir. The cut ends of the organ's inflow and outflow vessels are fitted with cannulae designed to marry easily with the tubes of the machine.

A blood gas analyser takes continuous measurements of the oxygen and carbon dioxide levels and pH of the blood as it makes its return journey to the pump. These measurements, made in real time, are used by the machine's internal controller to set the oxygen and air supply to the oxygenator.

Working livers secrete bile. Although this is ultimately discarded, the metra collects and measures the volume of bile produced: a useful guide to the functional state of the organ. Alongside all the other parameters measured, it provides what Coussios describes as an opportunity for the surgeon to 'test drive' the liver before reaching a final decision about its suitability for transplantation. With conventional cold preservation, the surgeon making this decision has little to go on other than the medical history of the donor and the overall appearance of the organ. Doctors using the metra have direct evidence of the organ's functional condition. Data on its viability can, if required, be monitored remotely.

The metra is nothing if not robust. It weighs some 80 kilograms, the consequence of a rigid wheeled base which, together with its batteries, allows it to be moved around the hospital and transported by road. It can even withstand lateral accelerations of several times gravity and can therefore be moved by an aircraft should it need to be. In a larger country such as the US, this option can be essential. Using cold storage, donor organs have to be implanted within eight hours, or 12 at the most. With normothermic preservation this time can be stretched to at least 24 hours and, if combined with periods of cold storage, to 36 hours or more.

OPERATIONAL AIDE

The real-world performance of the metra has found support in a clutch of clinical trials. One of the most significant was published last year in *Nature* and involved 220 subjects at seven sites in Europe. The trial was set up to compare the transplantation of donor livers allotted at random to conventional cold storage or to normothermic preservation using the metra. The study demonstrated that, even though 50% fewer organs were discarded in the normothermic arm and these organs were preserved on average for 50% longer, survival outcomes were not compromised and post-transplant liver injury was reduced by 50% in the recipient. As the authors of the study commented, "If translated to clinical practice, these results would have a major impact on organ utilisation, liver transplant outcomes and waiting list mortality."

The metra received its CE mark in 2016, and was granted approval by NICE (the National Institute for Clinical and Health Excellence) in 2019. It is now used in every transplantation centre in the UK, and in almost every country in Europe. An application for US approval is currently in progress. More than 550 livers have now been successfully preserved and transplanted in 11 countries. OrganOx is already well advanced on a machine for the normothermic preservation of donor kidneys, with a clinical trial due to commence in early 2020. The innovation made the shortlist for the Royal Academy of Engineering's MacRobert Award in 2019.

OrganOx is not alone in the warm preservation field; two other companies are active, but less far advanced. One measure of OrganOx's success is that all its original investors are still backing it, and it is still the only technology to have successfully completed a randomised clinical trial providing firm evidence of efficacy.

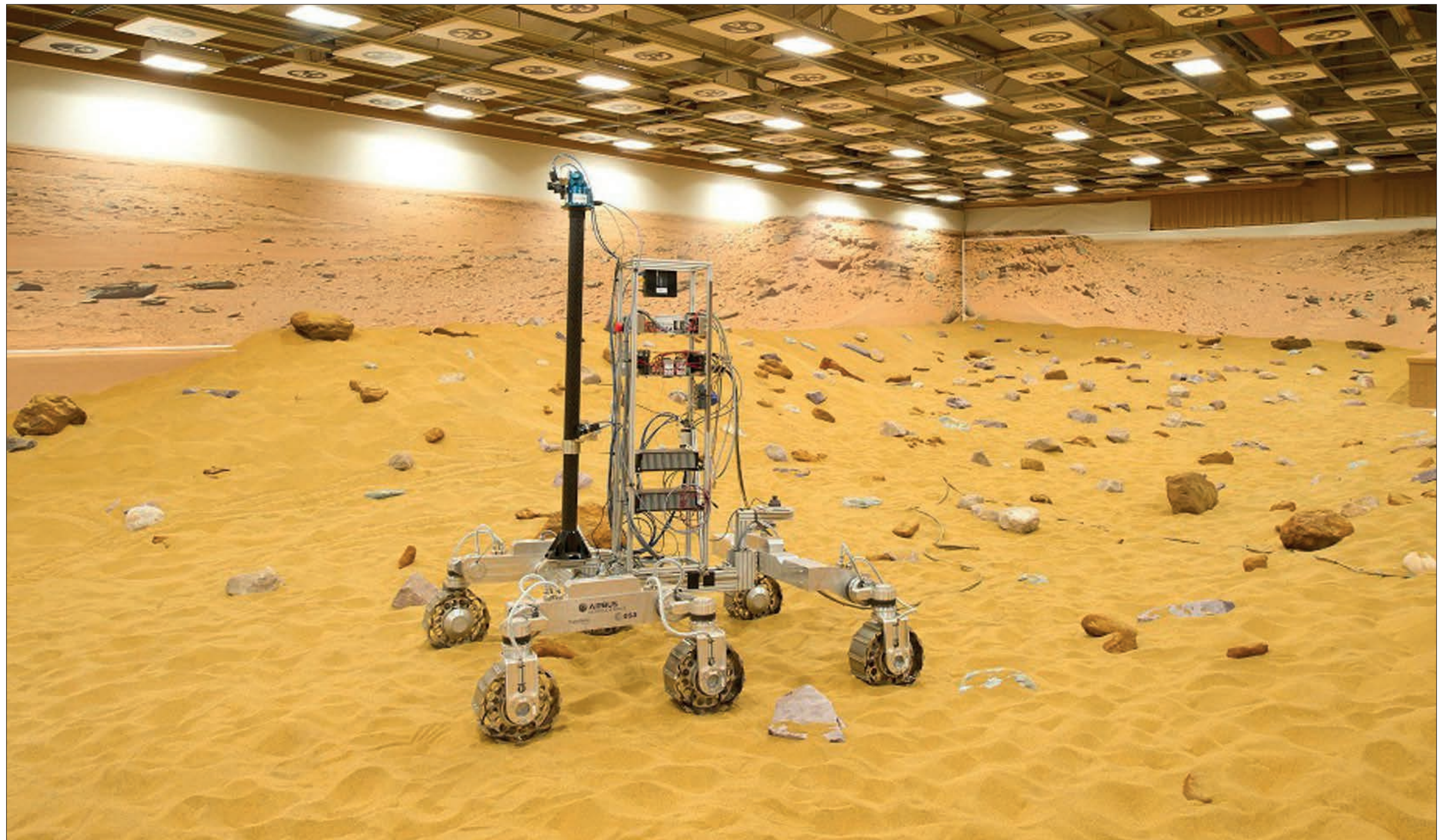
However, probably one of the most important outcomes is the fact that liver transplantation can now become a planned rather than an emergency procedure. The operation can now take place at a time that is best for the clinical team, patient and hospital. Medical journals have noted that this has several significant effects including reduced costs and more successful outcomes for the patient.

www.organox.com

BIOGRAPHIES

Peter Friend is Professor of Transplantation at the University of Oxford and Director of the Oxford Transplant Centre. He is a founder of OrganOx and Chief Medical Officer, with primary responsibility for the pre-clinical and clinical trials of OrganOx's patented normothermic organ perfusion technology. Peter's research interests lie primarily in novel applications of normothermic organ perfusion.

Constantin Coussios FREng is Professor of Biomedical Engineering at the University of Oxford and Director of the Oxford Institute of Biomedical Engineering. He is a founder of OrganOx and Chief Technology Officer, and leads the company's research and development activities. Professor Coussios received the 2017 Royal Academy of Engineering Silver Medal and was appointed as a Fellow of the Royal Academy of Engineering in 2019.



A prototype of the ExoMars rover being tested within the Airbus aerospace premises at Stevenage in 2018. Sixty different lights were installed in the 'sandpit' to match the Mars spectrum © Airbus

FINDING LIFE ON MARS

The UK has sent dozens of spacecraft to space, but has never successfully landed one on another planet. Tereza Pultarova spoke to UK engineers working on the European ExoMars rover about the technology that will enable some ground-breaking discoveries – including finding traces of what may have been life on Mars.

The PanCam being tested on the ExoMars rover in Airbus' cleanroom in Stevenage © Airbus, M Alexander

3.8 billion years ago, the planet Mars was not unlike Earth. Wrapped in a thick atmosphere, it had large quantities of liquid water on its surface and a strong magnetic field protecting it from cosmic radiation. But then something significant happened: the magnetic field disappeared and the atmosphere evaporated into space. Mars turned into the 'red planet' – dry, arid and hostile.

That significant 'something' happened at about the same time that first life was evolving on Earth, leading scientists to believe that, just like Earth, pre-climate-change Mars might have harboured primitive forms of life.

"The conditions on Mars then were very similar to the conditions on Earth then," said Professor Andrew Coates, of the Department of Space and Climate Physics of University College London (UCL). "We think that life could have started then because it had the same basic substances there as Earth had."

UCL's Mullard Space Science Laboratory is the UK's oldest and largest university-based space technology and research facility. Over its more than 50 years of existence, the laboratory has contributed to missions including the Jupiter-exploring spacecraft Cassini, a collaboration between NASA and the European Space Agency (ESA), and ESA's flagship space telescopes Herschel, XMM-Newton and Solar Orbiter.

A DREAM THAT STARTED WITH BEAGLE 2

For Professor Coates, the dream of helping to find life on Mars started in the 1990s when a team of British scientists developed the idea of the Beagle 2 Martian lander. The mission infamously failed upon landing on Christmas Day 2003, only to be discovered on the surface of Mars by a NASA orbiter 12 years later.

The stereo camera aboard Beagle 2, which Professor Coates and his team had developed, didn't get its chance to work. It did however provide the basis for PanCam (Panoramic Camera), an instrument dubbed the scientific eyes of the European ExoMars rover.

The rover, a pan-European project that was assembled over a period of 18 months by Airbus UK in Stevenage, is expected to launch in July 2020. It is the first rover designed specifically to find life on Mars, and has been named 'Rosalind Franklin' after the UK chemist and X-ray crystallographer who contributed to unravelling the double helix structure of our DNA. PanCam is one of nine instruments on board the rover that will work together to make that happen.

DRILLING FOR LIFE

PanCam, the only instrument led by a British team, will be the first to deploy once the rover lands in the Oxia Planum area, near the equatorial belt of Mars. While still sitting on top of the Russian-made Kazachok landing platform, the rover will unfold its solar panels. Then, a two-metre mast, with PanCam, NavCam (a set of navigation cameras) and

These are the filters that the ExoMars rover will use to view Mars in visible and near infrared wavelengths. They are pictured here in their individual transport cases, before they were installed in the filter wheels of the Panoramic Camera © UCL/MSSL, M. de la Nougerede

ISEM (an infrared spectrometer) mounted to the top of it, will be erected.

Spinning around on its pan and tilt head, PanCam will take its first panoramic image of Mars, which will be beamed to Earth for the ground control team to analyse and decide which of the landing platform's two ramps to use to commence the ground-breaking mission.

"PanCam is probably the main instrument of what we call the 'context instruments' on the ExoMars rover," said Coates. "It will provide us with the geological and atmospheric context. It will show us the landscape and help us see where there are potentially interesting rocks or features to explore and look for signs of life."

PanCam consists of two black and white wide-angle one-megapixel cameras sitting 50 centimetres apart, and a high-resolution camera for detailed inspection of rocks. Each of the wide-angle cameras has a wheel with 11 coloured filters in front of it, which will enable the researchers to image the surrounding surface at different wavelengths and build up the spectra in which the rocks reflect light.

"The filters are specifically dyed to be very good at looking for water-rich minerals like clays because that's where signs of life potentially could be," said Professor Coates. "It's the best ever camera to be sent to Mars with this purpose."

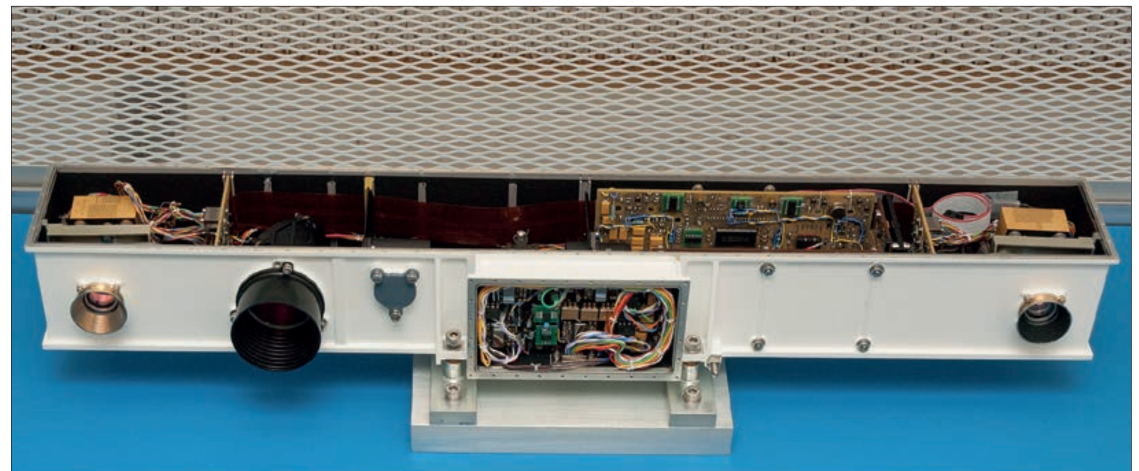
The scientists can send only 10 images a day to Earth. These images will be used to decide where to direct the rover next. In addition to PanCam and the infrared spectrometer, the rover carries seven other instruments. The close-up imager for detailed inspection of rocks is mounted next to the drill. The ground-penetrating radar and neutron spectrometer, both located in the rear, will provide information about the geology under the surface and the content of water in the ground. The Ma_MISS multispectral imager that will be located in the tip of the rover's two-metre drill will capture images as the rover obtains its sample. This two-metre drill is unique to the Rosalind Franklin rover. Its ability to drill up to two metres below the surface enables it to search for traces of life below the top layer of Mars, which is now a harsh place for life to exist due to cold temperatures and the presence of ultraviolet and cosmic radiation. Drilling to a greater depth than any of the previous rover missions will allow soil samples to be retrieved and analysed from an area where life might have been able to survive.

Inside the rover's analytical drawer are three instruments that will analyse the sample and look for signs of life – the MicrOmega visible and infrared imaging spectrometer for mineralogy studies; the RLS Raman Spectrometer for identification of organic pigments; and the MOMA organic molecule analyser that will look for signs of past and present life.

ON MARS ALONE

PanCam will also assist the two navigation cameras in generating input for the rover's autonomous driving system.

Navigation was one of the biggest challenges the consortium of engineers working on building the rover for ESA had to solve. Having learned valuable lessons from their American colleagues operating NASA's rovers, the engineers decided to give the Rosalind Franklin an unprecedented level of autonomy. Unlike the American rovers, the European rover does not have a direct link to Earth. It sends and receives data via the ExoMars Trace Gas Orbiter, which reached Martian orbit in 2016.



The PanCam engineering model in a clean bench, showing the fully integrated cameras and electronics © UCL/MSSL 2018, M. de la Nougerede

"We didn't want to effectively drive the rover like a remote-controlled car from Earth, which is either really inefficient or really dangerous because the time delay can be as much as 20 minutes in the worst case in each way," said Paul Meacham, Lead Systems Engineer on the ExoMars Rover Vehicle Project at Airbus Defence and Space.

"We built a system that allows the rover to drive itself, which is more advanced than that in the American rovers."

To be able to drive autonomously, the rover needs to be able to perceive the surrounding terrain in 3D. This is enabled by a set of two navigation cameras located on the optical bench on the mast. The navcams acquire black and white images every two metres of the rover's journey and just like the PanCam cameras, are relatively low resolution.

Meacham explains that when sending technology to space, engineers are working with processing capabilities equal to what was commercially available on the ground about 10 years ago. The process of space-qualification is costly and time-consuming and so cutting-edge science and engineering does not always have the most cutting-edge computing capabilities at its disposal.

"That's why we see in black and white rather than in colour because it's faster to process," said Meacham. "But the critical bit is that the cameras are very carefully aligned with respect to each other, so you can take the image from the right camera and the left camera and combine them together to produce a 3D picture."

That enables the software in the rover to judge the rover's position with respect to the objects in the image. The rover gradually builds up a navigation map of the environment replacing low quality data with higher quality data, as it gets closer to its targets.

The engineers trained the software on thousands of scenarios; driving in a computer-generated Martian terrain and simulating various situations the robot might find itself in.

"The digital model allows us to run these scenarios extremely quickly," said Meacham. "We can drive our rover over all sorts of situations, over hundreds of metres, we can crash it and then develop algorithms so that the rover handles all sorts of situations that it might encounter on Mars."

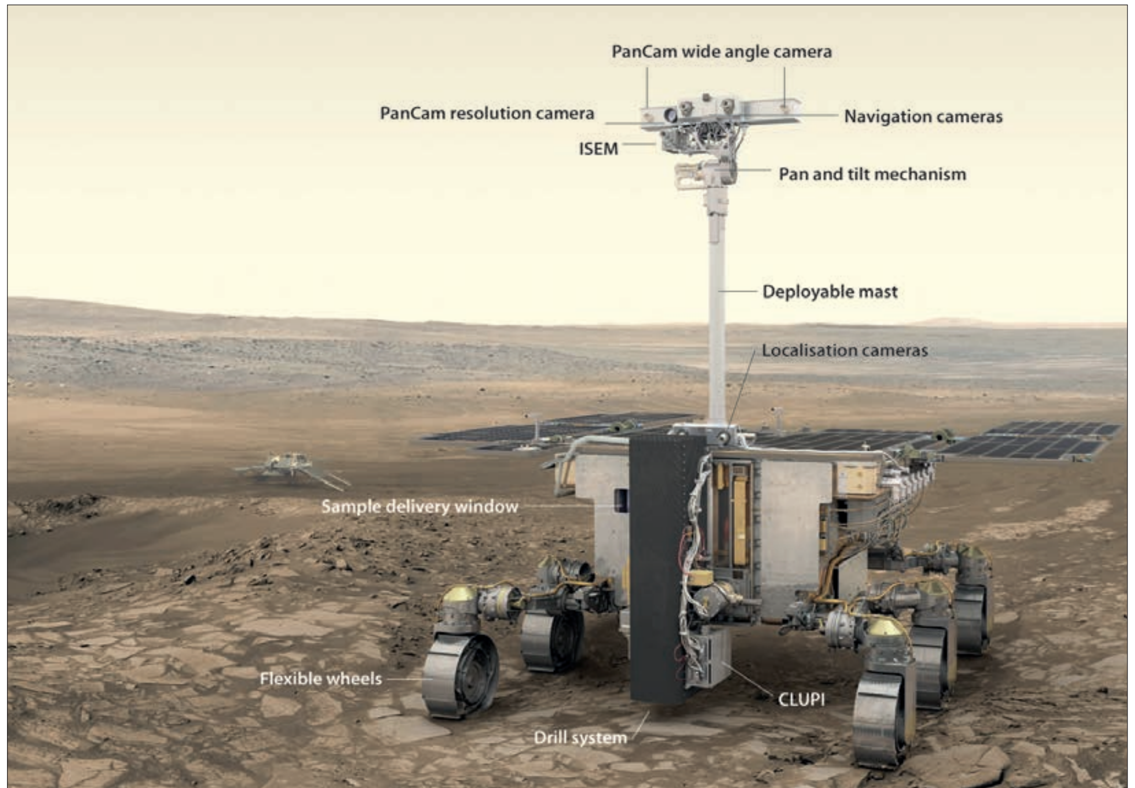
An additional two cameras, located at the base of the mast, take images as the rover travels to measure where it is located relative to the selected path. The software controlling this part of the autonomous driving process is, according to Meacham, similar to the Hawk-Eye system used in sports such as tennis, which tracks the trajectory of a ball and displays its most statistically likely path.

"It monitors a thousand points on the terrain in front of the rover and as the rover moves it sees where those points go and from that it can work out both its position and its attitude – pitch and roll," Meacham said.

After the software had proven its abilities in the digital models, the engineers verified it using ExoMars rover prototypes in the Mars yard – a giant sandpit mimicking the slopes and rock composition on Mars, which was built at the Airbus UK site in Stevenage.

FREEZING COLD

The Rosalind Franklin rover gets power from its solar array. The solar panels also charge a lithium-ion battery that powers the rover's critical systems once



A rendering of the ExoMars rover, which will be launched in the summer of 2020 and is due to land on the planet nine months later © ESA/ATG medialab

the Sun goes down. Martian days, known as sols, are 39 minutes and 35 seconds longer than Earth days, and there are 668 sols in a Martian year.

Especially in winter, the temperature at night can drop as low as −130°C. Daytime temperature in Oxia Planum could reach about 10°C. The extreme temperature difference the rover will be subject to can cause potential problems for all of its systems.

"Normally, satellite systems are only qualified to -50°C," said Tom Hunt, PanCam Systems Engineer at the Mullard Space Science Laboratory. "In orbit, where we send most of our technology, the temperature is relatively stable. But with Mars it's very different. We had to plan and test specifically for that."

Mars has a very thin atmosphere that doesn't keep the planet warm at night. On the other hand, the presence of an atmosphere causes the spacecraft to lose heat through convection, as opposed to radiation-only heat loss, which happens in orbit.

For the main body of the rover the Airbus engineers designed a solution that uses the same principle as double-glazed windows to prevent the convective heat loss.

"The main structure of the rover, which we call the bath tub, has a layer of cold gas trapped between the inner skin of the bathtub and a kapton baffle" said Airbus' Meacham. "We have also coated the structure in gold to stop heat loss by radiation."

But overheating during the day might be a problem too, Meacham said. With the rover's motors and multiple instruments possibly running at the same time, the engineers had to think about how to remove the excess heat if needed.

"We have a loop heat pipe, which takes the heat from inside the rover and transports it to a radiator, which has a white surface and dissipates the heat when we get too hot," said Meacham. "The loop heat pipe is filled with liquid that will evaporate on the hot end. The vapour travels along the pipe, condenses on the cold end and releases the heat."

The rover can turn the system on and off automatically, reacting immediately when the temperature changes.

The PanCam engineers had to design their own temperature control mechanisms since the mast doesn't fold back down after its initial deployment, leaving the optical bench completely unprotected. Due to the massive temperature changes, the 56-centimetre aluminium structure of the optical bench holding the two wide-angle cameras and the high-resolution camera could shrink by 2 millimetres. The shrinking and expansion of the material could easily damage the cameras' lenses, the filters as well as the electronics inside.

"Interfaces within the box have to be all from the same material," said Hunt. "If we need to use components that are from a different material, such as the optics, we have to match the thermal expansion or make mechanical thermal compensation devices so that the materials can be compliant to the movement due to the temperature."

Both of the wide-angle cameras, which had been developed by Thales Alenia Switzerland, as well as the high-resolution camera developed by the German Aerospace Centre, had to be thoroughly tested, together with all the electronics, circuit boards and interfaces.

The UCL team ran an extensive test campaign, using a refrigeration unit with liquid nitrogen to cool down the temperature of the device's sub-systems 320 times down to −130°C and warming it back up to +50°C within a few hours. The testing followed an accelerated method, which meant the cycle was much shorter than a Martian day would be, with the device only staying at the lowest temperature for 15 minutes. After every hundred cycles, all the solder joints and interfaces were carefully examined for the tiniest cracks.

The electronic components, all custom-designed, can operate down to a temperature of −50°C. The rover won't be operating at night, and it might take an hour or two after sunrise for the electronics inside the optical bench to warm up to the operating temperature.

Testing the Airbus UK prototype rover 'Bridget' in the caldera of Mount Teide, Tenerife in 2011, using the Aberystwyth University PanCam Emulator at the top of the mast © UCL/MSSL, A Griffiths

"We have quite a few local heaters, a few resistors that are used for heating various parts of the board," said Barry Whiteside, PanCam electronics systems engineer. "There is actually a whole heating sequence to get the instrument going. We will warm up a power converter and the control electronics first and once they are within the operating range, we can power the boards and then we use those to heat up the cameras individually."

BIO-HAZARD ON MARS

There is one other thing that has been completely new to the teams building the ExoMars rover and its instruments. Unlike spacecraft that only travel into space, the rover must be completely free from any Earthly microorganisms or even traces of organic material.

Planetary protection rules require space agencies to prevent polluting other worlds with terrestrial 'stuff'. For ExoMars, the impeccable cleanliness is even more important as any contamination could, in fact, wreck its mission.

"The previous Mars rovers, such as Curiosity, are geologists. We are the biologist," said Meacham. "Because we have instruments that are specifically looking for organic molecules in the samples, we absolutely cannot have any contamination."

Airbus built a new bio-clean room in Stevenage and introduced new procedures for all engineers working on the rover. The same took place at the Mullard Space Science Laboratory during the assembly of PanCam.

"There is a range of processes that all suppliers used to sterilise the components before they sent them to Stevenage," said Meacham. "Most frequently, they would use the dry heat microbial reduction technique that essentially involves 'cooking' the component at 125°C for 36 hours. Then we have to maintain that level of cleanliness throughout the build and test phase."

A NOBEL PRIZE?

If all goes well, the rover, which left Stevenage in August 2019, will launch for Mars in 2020 – the launch window is 26 July to 13 August. It will reach Mars in the spring of 2021. The engineers admit they will watch the landing with apprehension. Landing on Mars is an extremely tricky task. Of the nations that attempted the feat, only the US has so far been successful. The Beagle 2 mishap will be on everybody's minds, as well as the failed landing of Schiaparelli, an experimental landing platform sent to Mars with the ExoMars Trace Gas Orbiter in 2016.

"But we have to be optimistic," concludes Professor Coates. "If all goes well, we will discover that there indeed was life on Mars in the past and maybe get the Nobel Prize!"

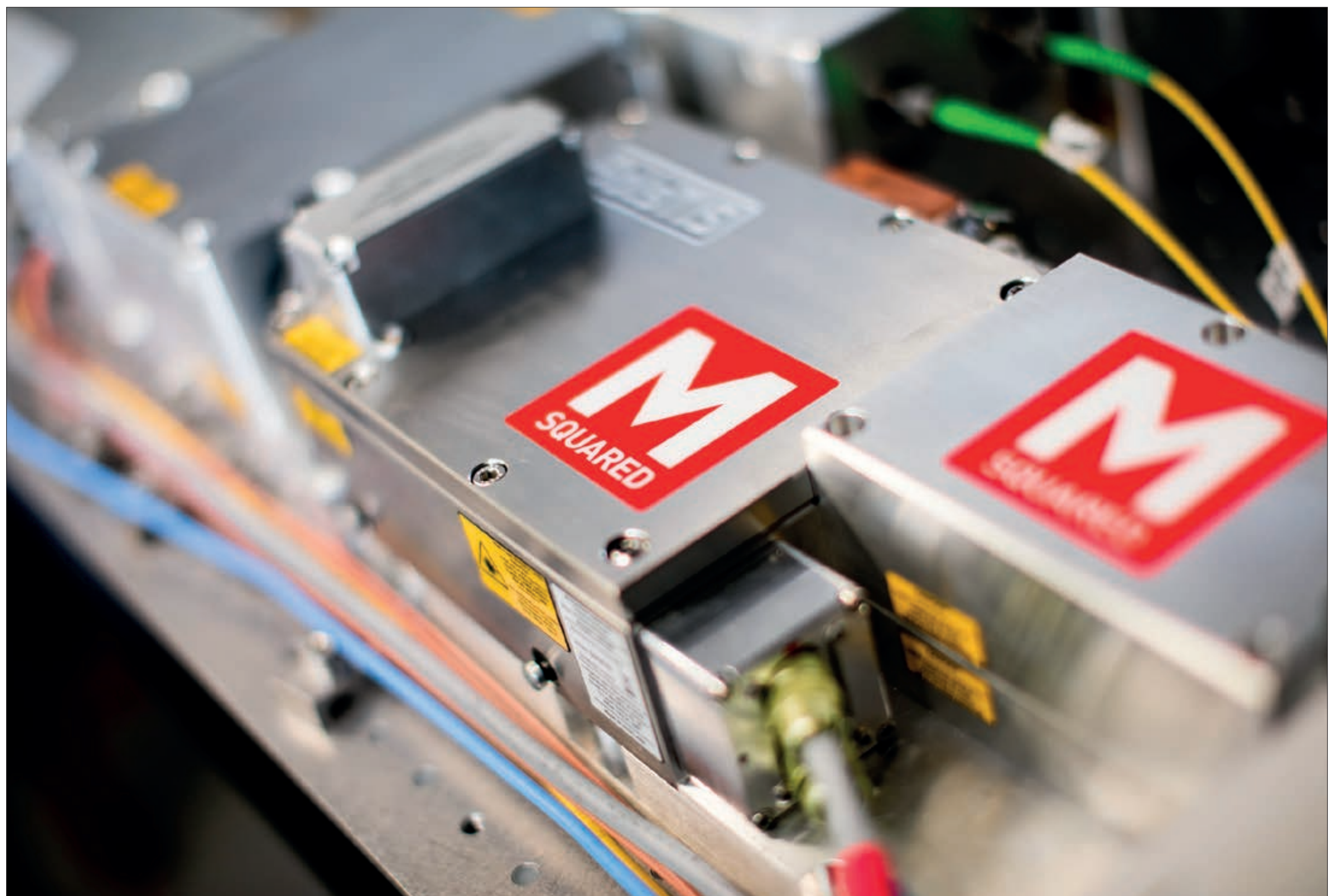
More information at **www.exploration.esa.int/mars**

BIOGRAPHY

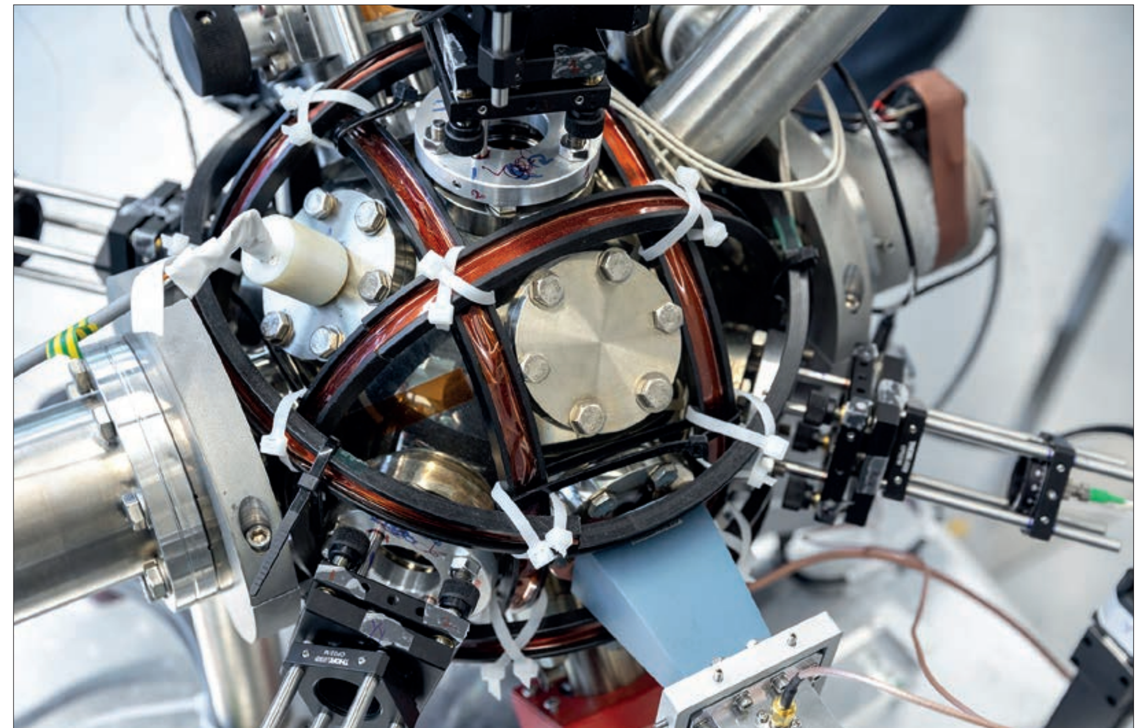
Professor Andrew Coates has been at UCL's Mullard Space Science Laboratory since 1982, with temporary positions at Max Planck Institute for Solar System Physics, Germany, University of Delaware, US and BBC World service. He is Deputy Director (solar system) at UCL-MSSL. He is PI of the Rosalind Franklin (ExoMars 2020) PanCam team. He was involved in Cassini, Venus Express, Mars Express and Giotto.

LASERS TO CHANGE THE WORLD

Enter any laboratory in academia or industry and there is a good chance that among their instruments, scientists will make regular use of a tunable solid-state laser from M Squared, using it for fundamental physics research. Born out of an academic research group, over the years M Squared has collected many awards for its lasers. Michael Kenward OBE spoke to Dr Graeme Malcolm OBE FRSE, CEO and Co-Founder, about the engineering that has made this possible.



M Squared's multi-award winning CW Ti:Sapphire laser system provides the world's purest light © M Squared



The SolsTiS laser is used in the world's most accurate clock, and could open the way to quantum computing
© M Squared

With "a mission to harness the power of light to change the world" no one would accuse M Squared of lacking ambition. Unlike a lot of sales pitches however, the company can point to numerous uses of its lasers that support its vision. Playing a central role in tackling climate change, SolsTiS was used to calibrate Tropomi, the spectrometer onboard the European Space Agency's (ESA) Sentinel 5P satellite that observes and maps critical atmospheric pollutants, including nitrogen dioxide, ozone, formaldehyde, sulphur dioxide, methane and carbon monoxide. In healthcare, the lasers allow the non-invasive study of cancers and degenerative diseases such as dementia, motor neurone disease and Parkinson's. Lasers are used for research in numerous scientific fields and industries, ranging from quantum technologies and semiconductors to chemical sensing and biophotonics and the SolsTiS is used by used by over 200 organisations in 30 countries.

It was, though, the engineering inside the laser that appealed to the judges of the 2019 MacRobert Award. Lasers tend to be sensitive devices that operate at nanometre dimensions. When researchers are working on, for example, breath analysis, the last thing they want to do is to have to retune a laser when it gets bumped. Before SolsTiS, scientific lasers were largely experimental in themselves.

It takes clever engineering design to create laser systems that can deliver "the highest purity light yet produced anywhere in the world". M Squared's SolsTiS system stands out because of its precision, compactness, ruggedness, reliability and turnkey operation. SolsTiS delivers a step-change in continuous-wave laser technology, delivering single mode laser light with an ultra-narrow linewidth. The system is also fully automated and widely tunable, connected to the internet and operated via a webpage. All of this sits in a completely sealed unit that needs no alignment by the user.

FROM RESEARCH TO PRODUCT

M Squared had its origins in Dr Graeme Malcolm OBE FRSE's PhD project on compact lasers at the University of Strathclyde. The university has a long reputation as a leading centre of research and innovation in laser technology and optoelectronics and was at the centre of Scotland's optoelectronics sector. In 1992, Malcolm, along with Dr Gareth Maker, set up Microlase Optical Systems to turn their research into usable products. The two did not have to wait long for orders to come in. Indeed, they set up the business partly because, as research students, they were already supplying systems to other research groups.

As Malcolm put it at the time, "We were effectively pioneering the research we were doing at the University of Strathclyde then. Older generations of devices were six-foot long, highly complex and you needed a PhD to operate them. They needed 50 kW of power, were the size of a filing cabinet, and required gallons of water to keep them cool."

Equipment like that wasn't the sort of thing that anyone but a laser researcher would deploy as standard kit in their academic laboratory, let alone in industry. Malcolm and Maker wanted to develop a self-contained diode-pumped laser that was smaller than a shoebox – you could just plug it into the mains and light would come out.

In 1999, the global laser businesses Coherent Inc. bought up Microlase Optical Systems and Malcolm became head of Coherent Scotland. This gave Malcolm and Maker the resources needed to develop the business. They could move on from selling lasers to laser scientists and begin the laser's transformation into a usable and reliable device that non-specialist engineers could use almost as routine components in complete systems for whatever applications they had in mind that needed a very pure source of coherent light. They also moved into new wavelengths, and very short light pulse lasers, to broaden the range of applications, such as biomedical imaging.

In 2006, Malcolm and Maker left Coherent Scotland to set up another company to develop a laser system based on research at Strathclyde and elsewhere. The new company was M Squared, which gets its name from the two founders and the M2 parameter known as a laser's 'beam quality factor'. The idea was to produce a compact and totally automated version of the single frequency Ti:Sapphire laser, the optical 'engine' inside the SolsTiS system.

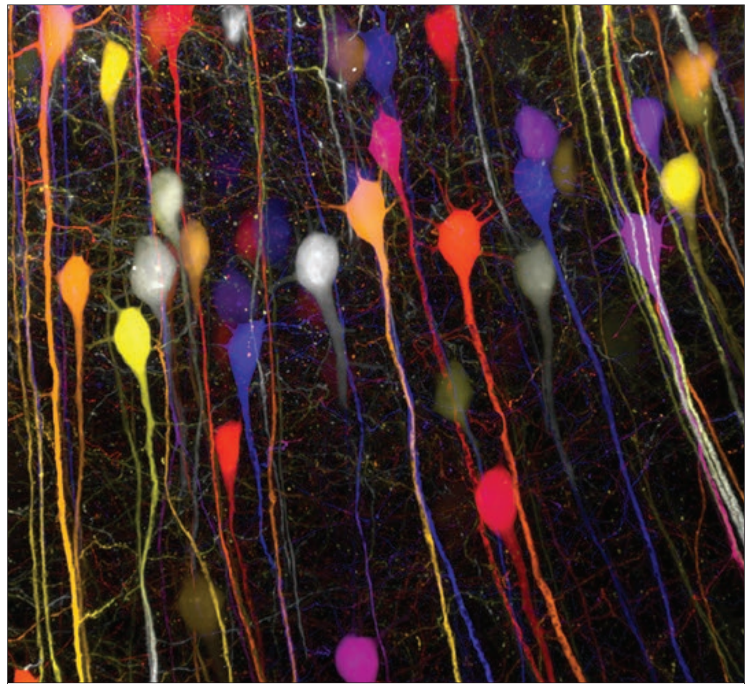
It wasn't just the laser that came out of M Squared's work. The company also worked to make its systems easy to use. For example, as long ago as 2006 they had worked out how to run it from a webpage with an internet connection.

CHALLENGES OVERCOME

As well as active and passive dimensional control in the nanometre range, the engineers had to isolate the optical components from vibration created by the circulated water cooling. The design of the hardware also had to isolate the optical elements from temperature variations and physical impact.

SolsTiS also required optical innovations to fit a long optical path into a small space, using a 'bow-tie' arrangement of four mirrors. Additional optical elements in the light path refine the light output so that the laser output has an extremely narrow linewidth – the narrowest of any commercial system – and is single mode across its whole tuning range. To do this, the engineers not only had to devise their own approach to mounting the optical components to maintain the stability of the system, but also develop precision adjusting elements and control software to compensate for uncontrollable movements as well as enabling wavelength tuning. It was, says David Delpy, MacRobert Award judge, "a truly impressive piece of kit operating at unprecedented levels of accuracy and reliability. It takes an enormous amount of engineering to get the optical system right to enable it to do this".

Much of the innovation was in the application of novel physics and mechanical engineering to create continuous-wave and tunable laser light on an unparalleled 'small' scale. The parts were designed from scratch. Beneath these engineering achievements sits an enormous number of careful design measures, such as the use of a minimum number of easily-cleanable materials to control thermal expansion and that do not absorb or emit gases that could escape into the cavity and disturb the laser's output. Even the laser crystal light source required careful engineering, with a unique slab design of optical material, chosen to deliver the required tuning range, and held rigidly in a stress-free mount. The company holds more than 400 patents on the innovations that went into the system and the areas in which it is used.



The engineering behind SolsTiS supported the development of the Aurora light sheet fluorescence microscope, here showing an optically cleared mouse brain expressing thy1-GFP Actin, maximum intensity projected using a coloured height map © Dr Anthony Vernon and Robert Chesters, King's College London

APPLICATIONS: SPACE AND TIME

Beyond being a finalist in this year's MacRobert awards, the success of M Squared's engineering shows in the range of applications for the SolsTiS lasers. At one stage, atomic clocks were a big market for the lasers. The US National Institute for Standards and Technology (NIST) used them in the world's most accurate clocks, giving an accuracy of one part in 10^{18}, equivalent to a second in the lifetime of the universe, says Malcolm. Atomic clocks are already used in areas ranging from financial trading to navigation.

In their assessment of the laser's clear societal benefits, the judges of the MacRobert Award also noted its use in the accurate calibration of instruments for Earth observation satellites, allowing observations of polluted areas on earth from space, accurate to a five-kilometre square. As the judges put it, "concentrations of formaldehyde, nitrogen oxides, methane and carbon monoxide can now be monitored from space for the first time." In fact, M Squared was approached by the ESA with an emergency request – design a solution for monitoring CO_2 from space – and the SolsTiS delivered. The lasers were used to calibrate the Trompomi telescope on the ESA satellite Sentinel 5P before launch, the first industrial laser for earth observation.

One sign of the commercial success, and promise, of the SolsTiS technology is the growing market for the laser and its associated systems. What started off as a must-have instrument for university physics laboratories and national laboratories has moved on. Industrial applications now make up the largest market. Semiconductor applications that require laser cutting of stencils for sub-micron-sized components, using laser-based machine tools, have been designed in collaboration with M Squared.

M Squared has also branched out of the world of physics and engineering into the life sciences. For example, the engineering behind SolsTiS also supported development of the Aurora light sheet fluorescence microscope. The company designed this system for researchers working in fields such as neuroscience, developmental biology, cancer biology, regenerative medicine and other bioscience disciplines. With Aurora, life scientists can accurately image large structures at cellular resolution, measurements that are fundamental to modern biological understanding. The technology also enables life science imaging at individual cell level, including neurons in the brain.

The company says that its lasers have enabled breakthroughs in areas as diverse as dementia research, cancer diagnosis and whiskey maturation. In 2015, M Squared opened a specialised biophotonics division, M Squared Life, on the Surrey Research Park.

QUANTUM TECHNOLOGY

More recently M Squared has moved into another area where research meets engineering, quantum technology. M Squared describes SolsTiS as "the backbone of many quantum technology systems and experiments". The laser's ultra-pure light and low noise makes it "the ideal tool for quantum experimentation, where excess noise can easily destroy the subtle effects that quantum technologies seek to exploit."

The team maintains that SolsTiS is "the de facto standard laser system used in the development of quantum technologies and experiments". It is also used extensively in several approaches to quantum computing, including leading research at Oxford, Sussex and Innsbruck universities. SolsTiS is also responsible for many new advances in quantum sensing. M Squared likes to describe SolsTiS as the backbone 'engine' behind much of its work, for example, on the UK's first commercial quantum gravimeter to detect underground objects and a quantum accelerometer for GPS-free navigation. The quantum accelerometer uses SolsTiS to suspend and release atom clouds.

One sign of the expectations for quantum technology, and the company's commitment to the area, was the recent announcement that M Squared has opened a new quantum research facility in Glasgow. Hosted by the University of Strathclyde, the new quantum research centre is in the university's Inovo building in Glasgow City Innovation District. At the time of the announcement, Derek Mackay, Scotland's Economy Secretary said: "Our economic development agency Scottish Enterprise recently awarded a £2.9 million R&D grant to M Squared to help accelerate their cutting-edge research… [It] will support 24 new jobs, help realise Scotland's quantum potential, and enhance our ability to compete globally." Also commenting on the announcement, Malcolm said "We are on the verge of a second quantum revolution whereby the counter-intuitive behaviour of physics at the atomic scale will be harnessed to create the defining technological advances of the future."

M Squared has grown to have a turnover of more than £20 million a year and employs more than 100 people, most of them in technical roles. The business is doubling in size every two or three years, fuelled by reinvesting 10% to 20% of its revenue in R&D. SolsTiS accounts for 85% of the company's sales.

"The huge promises of quantum technologies are already starting to become tangible," says Malcolm. In the MacRobert Award judges' view, these developments in quantum technology "will most likely underpin the next transformative large-scale economic transition". It is, then, perhaps no surprise that one magazine described M Squared as the company that "sells the shovels for the quantum gold rush".

QUANTUM ACCELEROMETER FOR NAVIGATION

One development in the rapidly rising realm of quantum technology is M Squared's work with Imperial College on the UK's first commercial quantum accelerometer for navigation. The accelerometer uses quantum interference of matter waves to measure horizontal accelerations with ultra-high accuracy. It identifies its starting location, and precisely measures acceleration from there. As the company puts it, "The purpose of this is to navigate ships and submarines, and perhaps other vehicles in the future."

The global navigation satellite system (GNSS) that underpins many location systems is susceptible to disruption or denial, either deliberate or natural. Estimates suggest that interfering with GNSS for a just five days could cause £5.2 billion of economic damage to the UK alone. "Quantum sensors, including our accelerometer, offer a new way to achieve accurate navigation without the need to send communications back and forth to satellites," says M Squared.

M Squared and Imperial College are developing a commercial quantum navigation system. Their aim is to achieve the highest possible sensitivity and to provide accurate positioning, even over long journeys. Their quantum accelerometer recently showed a positional accuracy within 2 kilometres after one month's use, a substantial improvement in state of the art accelerometry.

Imperial College London and M Squared has produced the world's first transportable, stand alone quantum accelerometer incorporating the SolsTiS system © Thomas Angus, Imperial College London

BIOGRAPHY

Dr Graeme Malcolm OBE FREng FRSE is CEO and Co-Founder of M Squared, a multi-award-winning photonics and quantum technology company. He is a Fellow of the Royal Academy of Engineering, The Royal Society Edinburgh, and the Institute of Physics and his achievements include an OBE for his services to Science and Innovation, the Swan Medal from the Institute of Physics, and Entrepreneur of the Year at the Amazon Growing Business Awards.

CLADDING CROSSRAIL'S TUNNELS

The new tunnels built for London's huge Crossrail development were coated with a sprayed concrete lining. This resulted in a rough and variable fixing surface that needed an innovative engineering solution to fit the cladding system to the inconsistently-shaped tunnel interiors. Tamar Collins spoke to Board Director Jaimie Johnston and engineers at Bryden Wood about how they overcame the project's challenges.

The fitting out of the Elizabeth Line stations on the London Underground included the creation and installation of glass fibre reinforced concrete cladding panels. These were used to negotiate and accommodate complex shapes as well as to ensure structural strength © Crossrail

Laing O'Rourke asked Bryden Wood to evaluate the detailed design and installation of the intended cladding for Crossrail's tunnels. The company's findings were so significant that it was commissioned to develop the design and installation principles of the cladding system for three of the largest and most complicated stations – Tottenham Court Road, Liverpool Street and Whitechapel.

THE TRADITIONAL APPROACH

The sprayed concrete tunnel linings for the Crossrail platform and crossover caverns for the stations were applied at an earlier stage of the project. The concrete lining created spacious circulation routes but is not an ideal final finish for the tunnels as it can be inconsistent, dusty, hard to paint and is acoustically 'bouncy,' causing sound to clatter and echo. The tunnels needed cables run through for power, lighting, fire detection and alarms, data, and other services, which had to be covered up for aesthetic purposes and to prevent tampering while still allowing access for maintenance and replacement.

On the London Underground, tunnel cladding is normally done with tiles or powder-coated steel panels. Cladding manufacturers and installers contend with vast amounts of variation on construction sites and so systems need to be flexible. General construction allows a 'plus or minus 10 to 20 millimetres' level of variability between measurements and production, with the assumption that every fixing (of thousands) will require adjustment. Traditional methods would have risked a slow, labour-intensive and expensive process with a big margin for error. The site was long and narrow, with virtually no room to manoeuvre heavy equipment or stockpile materials. Moreover, constant drilling and fixing into the concrete lining would have created health and safety issues. A new approach was needed.

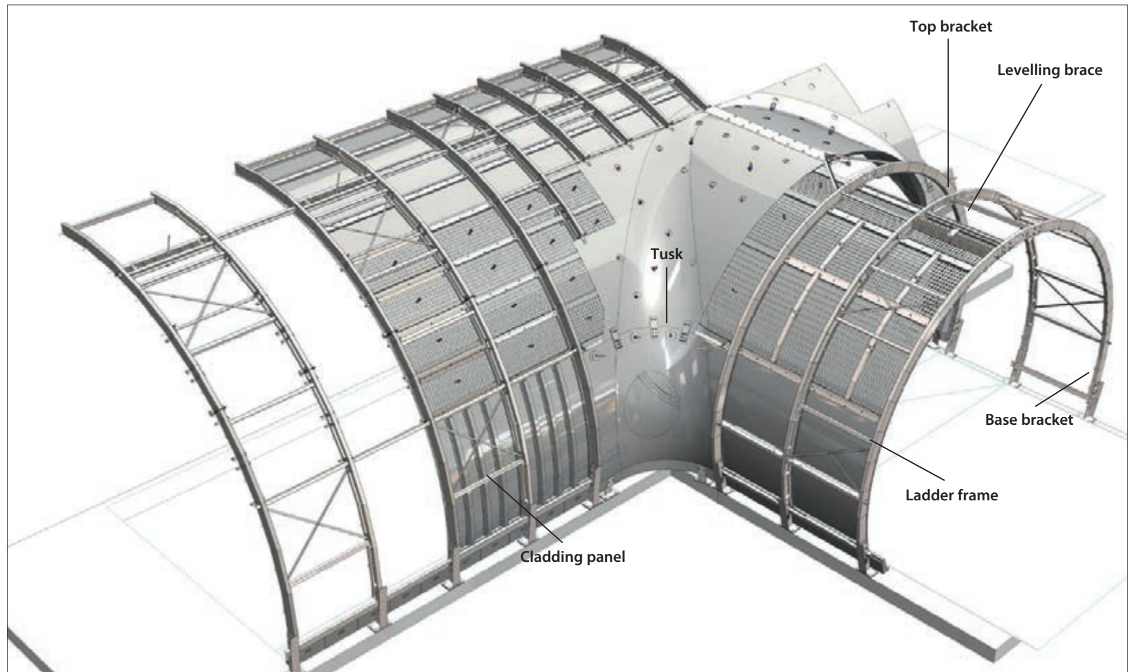
There were three key aims for the project design: maximum health and safety, maximum productivity and maximum accuracy. This fed into the design of the 23,000 cladding panels. The team aimed to ensure that the detailed engineering and industrial design took place at the beginning of the process. They brought the design team into one office onsite, enabling fabrication design problems to be solved during the planning stages. The key was to get it right first time and then install it once, rather than having to fix things as the project went along.

In contrast to the standard 20 millimetres of tolerance, the team worked with a 'zero tolerance' approach to ensure that the manufacturers were as accurate as possible. Although they knew 'zero tolerance' wouldn't be fully achievable, setting such ambitious standards was highly effective, ultimately achieving a 70% tolerance reduction (3 millimetres), when compared to traditional construction. Finally, they used an entirely digital workflow, producing all of the design work in 3D digital formats, eliminating the production of fabrication drawings and potential for human drawing errors. All subsequent reviewing and commenting were also done digitally.

The goal was to develop an engineering solution to minimise fixings into the sprayed concrete lining. The breakthrough solution would create the new 'zero tolerance' methodology, provide lighter panels, use less materials, quicken installation and lessen the risk of injuries.

THE NEW APPROACH

The key elements of the cladding system and the planned sequence of installation were developed in tandem. The solution is a stainless steel ladder framework that holds the glass fibre reinforced concrete



Junction transition: the intersection of two tunnels. The larger one is the platform and the smaller one is the entrance to the platform from a central concourse © Bryden Wood

(GFRC) cladding panels. The complex intersections where two tunnels meet, known as 'junction transitions', required special joining pieces known as 'tusks.' Top brackets were fitted to the crown of the tunnel and a levelling brace was attached to the brackets. Next, base brackets were installed to the platform. The ladder frames were then installed between the base brackets and the levelling brace, before finally, the cladding panels could be fitted to the ladder framework.

LIGHTWEIGHT CLADDING PANELS

The cladding panels are mostly curved in one plane, although some are curved in three dimensions. A range of panel types were used, some solid and others perforated to include acoustic lining. Cast from GFRC, the panels are composed of tiny, high-strength glass fibres, surrounded by a concrete matrix. The concrete protects the glass fibres and helps carry the load – to some extent acting like the steel reinforcing bars in traditional reinforced concrete. The result is a durable material that can be cast to a very fine and decorative finish but is nearly two-thirds lighter than traditional concrete.

The lighter panels required fewer fixings and a lighter supporting structure resulting in less load being carried. They also need less material, cost less and emit less carbon in their making. The panels are quicker to make, because thinner concrete sets more quickly, and if light enough, can be manually handled, which eliminates the need for machinery.

Bryden Wood used SolidWorks to develop the design, a software more typically used in manufacturing, product design and industrial design than in construction. This allowed the density of the material to be modelled and the weight and centre of gravity of each panel to be calculated. This led to the lightest possible design that nevertheless safely met all of the technical requirements, with the panels meeting exceptionally high-performance targets for fire, bomb blast and impact resistance. Importantly, the combined weight of the panels and supporting structure met the construction criteria for two-person-handling, eliminating the need for heavy lifting equipment.

FIXING THE PANELS

The cladding panels are fixed to a secondary structure to support the weight and to position them accurately. The entire cladding system needed to sit within 250 millimetres of the wall, a challenging proposition when holding several tonnes of concrete in the air.

At the bottom of the cladding, the secondary frame can sit directly on the platform, but the top must be fixed into the sprayed concrete lining, a challenge due to its rough finish and inconsistent thickness. Manually drilling into the concrete, particularly at height, risks injury and is almost impossible to do with millimetre accuracy. The secondary frame overcame the inaccuracy of the concrete spraying and created a highly accurate positioning system for the panels.

The secondary structure is created from steel 'ladder' frame structures and cast GFRC arched 'tusks', depending on which suited the situation – both have merits. Brydon Wood's designer Thomas Nunn says "Concrete arches take advantage of the monolithic approach, where you have one complex object that does all the work for you, versus building it out of steel… which also has its merits – they come in small pieces, you can assemble them with less assisted machinery… If one element has a problem, you can replace a small element, rather than having to replace the whole thing or repair it."

This image shows a GFRC 'tusk' in the foreground with the standard 'ladder' frame in the background © Bryden Wood

The most commonly-used secondary frame was the series of steel 'ladders'. Reducing the amount of fixings to the concrete reduced the impact of potential movement of the cladding system over time. Fewer fixings would mean less stress on the system in the event of tunnel movement. To minimise fixings into the sprayed concrete lining, Bryden Wood fixed adjustable brackets to the concrete crown of the tunnel at 4.5 metre intervals to support a levelling brace. This was lined and levelled using a laser beam to ensure it was precisely positioned (+/- 0.0 mm) in *x*, *y* and *z* coordinates. This brace would form the support for the top of the ladder frames, so that instead of having to fix every ladder into the sprayed concrete lining, operatives only had to install the single, straight rail – a far easier, safer task.

For the fixings at the bottom of the frame, adjustable brackets were fixed into the platform rather than the sprayed concrete lining. A laser beam was then fired along the tunnel for the final adjustment to be carried out.

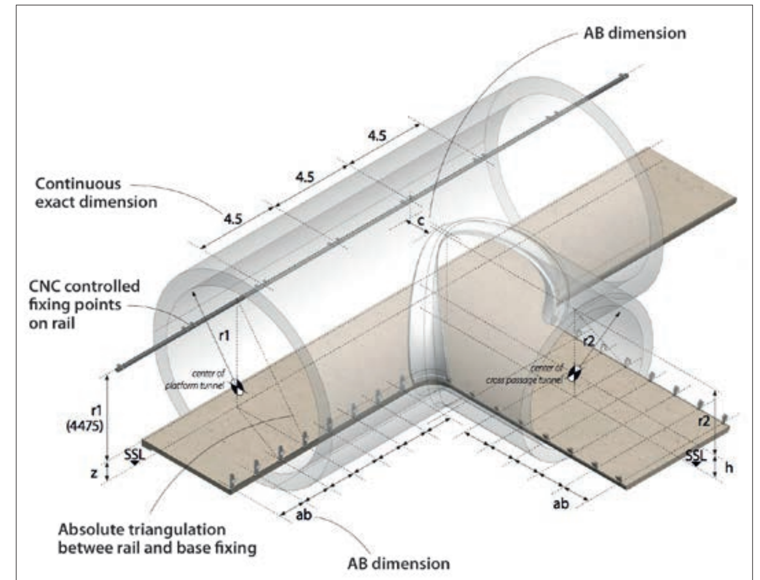


Diagram showing the setting out and installation strategy for the adjustable brackets and rail at the crown of the tunnel and the base fixings © Bryden Wood

To avoid any issues with corrosion over the planned 120-year life of the project, the specification for the frames stipulated stainless steel. Rather than fabricating the frame, usually done by welding sections of steel together, it was laser cut and folded from a single sheet of stainless steel to ensure accuracy.

Complex shapes, such as the double-curving shape that occurs at the junction of two tunnels of differing diameters, made it too difficult to align and bolt steel elements together in the precise shape required. Instead, GFRC supports with internal high-precision fixing points were cast using moulds. Casting in a single material removed a huge amount of fabrication time and removed the risk of inaccuracy.

AUTOMATED MOULD MANUFACTURE

During construction, Laing O'Rourke GRC UK Ltd designed and manufactured 2,300 moulds for the cladding panels over a two-year period. Laing O'Rourke used five-axis computer numerical control robotic milling machines, which carved the larger moulds. This process was driven automatically, with Bryden Wood's models driving the machinery. The mould-making itself was no longer the slowest part – instead it became how quickly the designs for the moulds could be created.

At peak panel production, 350 panels were cast a week to achieve the deadline.

Moulds created directly from the design model. On the left is one of the smaller moulds which could be created using 3D printing. On the right is the mould for one of the tusks – these were computer numerical control-machined from glass reinforced plastic © Bryden Wood

A mould was made for each new panel shape, and moulds could be repeatedly sprayed with GFRC. As each tunnel was slightly different, every bend had the potential to introduce an additional 80 to 100 panel types, which could have resulted in hundreds of thousands of pounds of design and mould-making. Digital exercises were carried out to achieve repeatability, using only small tolerances between the panels to take up the variation. The repeatability of panels was a huge cost saving, and the team made a significant effort to try and optimise the shape across the three stations.

INSTALLATION

The final steps of the installation process were checked digitally, to avoid issues on site. While most components could be 'pre-kitted' and delivered on pallets to site, the larger tusks went through an additional level of checking. Cranes dropped the components down shafts to the platform level below ground. The entire process of delivery to site and the path to site was tested before it happened using virtual models.

When it came to setting out the steel ladder framework, precise coordinates in virtual 3D space were provided down to the millimetre, again generated from the model. Engineers identified the key points on each assembly and standard construction instruments were used to position the key points precisely. With the base bracket positioned accurately, everything fixed to it could be placed in exactly the right position without extra setting out work.

The installation of the architectural feature known as the 'Trumpet' at Whitechapel and Liverpool Street station (a large vertical GFRC wall that transitions with double curved panels in the escalator barrels) required two lasers to create a point that indicated where to position the adjustable bracket. The model was clicked on to position the lasers and the installers could then appropriately position the right corner of the bracket onto the cross section.

A NEW ERA IN CONSTRUCTION

This technology and workflow plan has since been applied to precast facades for buildings on the Shell Centre in London and St James's Place in Edinburgh by Bryden Wood and Laing O'Rourke. On both projects, the digital modelling allowed the most aesthetically-pleasing design to be created and evaluated before manufacture. By using industrial design for fabrication, a digital workflow and automated assembly, the Crossrail cladding package was delivered on budget and on time, while also improving health and safety.

The focus on efficiency and innovation delivers standardisation. Gradually, projects such as this are leading the industry towards a new era. Without compromising aesthetic integrity, architects and engineers are now looking towards a future of building faster, more economically and with better whole-life value.

BIOGRAPHY

Jamie Johnston is Board Director and Head of Global Systems at Bryden Wood, where he leads the adoption of a manufacturing-like approach to creating high performing assets on projects.

Sam Bromley is a design engineer at Bryden Wood, with specialist experience in sheet metal, timber, and structural steel.

Thomas Nunn is a mechanical engineer who worked on the project using high-quality computer-aided-design.

Stephen Temple's work has changed modern communications, from his role in implementing early mobile communications networks to his current focus on 5G

A SPECTRUM OF GENERATIONS GAMES

Engineering innovations come from many sources, even from the work of civil servants. For Professor Stephen Temple CBE FREng, working as an engineer within government was an opportunity to shape modern telecommunications and lay the foundation for today's trillion-dollar global mobile industry. He talked to Michael Kenward OBE about a career that has spanned the history of mobile telephony and his recent experience of rescuing 5G from a bureaucratic black hole.

Civil servants working behind the scenes can be crucial to the introduction of revolutionary technologies that have long-lasting social, economic and commercial impacts

Young engineers with ambitions to change the world are hardly likely to think of a career in the civil service. Could a job in Whitehall help launch spacecraft, create new energy sources or lay the foundations for essential physical infrastructure? Professor Stephen Temple CBE FREng found that civil servants working behind the scenes can be crucial to the introduction of revolutionary technologies that have long-lasting social, economic and commercial impacts. For him, it happened more than once in his work on mobile telecommunications. The first was in 1987 with his ground-breaking GSM Memorandum of Understanding (MoU) that launched GSM (the Global System for Mobile communication) across Europe. More recently in 2016, Temple found a way to bridge a bureaucratic radio spectrum void that was to change the direction of 5G mobile networks in Europe.

The underlying theme in both "simple inventions", as Temple describes them, was how policymakers can couple radio spectrum to a new generation of mobile technology. Spectrum allocation, an area where governments have a lasting interest, is the make or break decision for telecommunications: satellite links, radio and TV broadcasts, police communications and, these days, mobile telephones, all rely on the ability to use an area of the spectrum without fighting off interference from other uses.

When Temple entered the fray, personal mobile telephones were still science fiction. Domestic telephones were strictly analogue. Even the switches used to place and route calls were mostly mechanical when Temple began his training as an apprentice at Marconi. At first, his career followed a traditional pattern. After completing his MSc in electronics at the University of Southampton he returned to Marconi, working as an engineer on satellite systems. He took note when a colleague suggested that, in the early stages of their careers at least, engineers who want to go places shouldn't hang around too long in one job.

MOVING ON

Temple took this on board. When he had fulfilled his obligations to Marconi he sent job applications to several engineering companies, along with one to the civil service. The responses confounded his expectations. The civil service was quicker on its feet than industry and before any of the companies had even replied to his applications Temple had been interviewed and offered a job in the Ministry of Posts and Telecommunications. "Within a couple of months of joining the civil service I found myself at the 1971 World Administrative Radio Conference." He was instantly the leading expert on spectrum sharing between satellites and radio relays. Temple admits that it was a steep learning curve. "The MSc was good training because it did allow you to dive into the deep end of something that you knew nothing about."

It seems to have worked: Temple's growing reputation for international technical negotiation landed him a job chairing a group preparing for the 1977 broadcasting satellite conference. "Anything to do with broadcasting in those days was really political," he says "and I was a naïve engineer with much to learn about global disputes and tensions, some even within Europe." During these international activities Temple came to see the power that engineers could potentially have in the civil service. The tradition in the UK is that civil servants advise and politicians decide. Temple realised that maybe there could be more to a career than doing a good job and the next promotion. "Suddenly the world opened up and perhaps my ambition should actually be to shape my country's future."

He came to realise that engineers in the civil service are well placed to make decisions that make a real difference to the country. Few politicians will understand engineering issues, let alone have a policy view on them. But as Temple points out, an engineer working in that environment has to understand politics, economics, the relevant industry and technologies. "If you could bring all of those together, there comes a point of change, and if you have a supportive minister that is up for doing something ambitious in your field, you can set a new direction for the entire country.

INTERNATIONAL STANDARDS

Sometimes you have to manoeuvre yourself into a position to achieve that ambition. One less common way to achieve this is to spot a new need and write your own job description for it. Seeking a way out of several years in what he dubs a treadmill telecoms job in the Home Office, Temple came up with an idea that would put him back into international affairs. The government planned to privatise British Telecom in 1984. As a state industry, British Telecom had represented the UK in international standards bodies. As Temple saw it, the task of representing the UK's national interests belonged back in government. "You couldn't have BT wrapping up new international standards to suit its own interests but not those of its new competitors. It seemed to me that that was not consistent with a competitive infrastructure market." So, in the run up to the privatisation, Temple decided to write his own job specification. "I wrote to the undersecretary out of the blue to say I think you have a need for a senior technical person to lead and represent the UK in all the international standards bodies."

In 1987, Stephen Temple helped produce a quadripartite agreement between Germany, France, Italy and the UK that committed them to a common strategic vision for Europe's mobile radio infrastructure and lit the fuse for the GSM revolution. It was signed in Venice in 1987

Temple moved to the Department of Trade and Industry, where he found that the international negotiations on the next generation of mobile communications, GSM, were bogged down in European national politics. There then began a long saga as countries and companies fought to get their ideas adopted (Temple has described the process in detail in his book *Casting the Nets: From GSM to Digital TV*). The political breakthrough came in the choice of technology. A spectrum band had been found for GSM. But nobody had worked out how it would be launched and survive in the still fragmented national markets, where fierce competition was coming very fast around the corner. Temple was one of the first to spot that "instant" scale for mobile phones would be the difference between life and death. He had to invent something quite new: it had to finely balance cooperation with competition. His solution was set down in one of the most important documents to come out of the mobile industry – the GSM MoU.

Temple likes to describe the GSM MoU as the "invention of a *risk-free* high-tech delivery model". It does this by bringing together a critical mass of network operators willing to take the high-tech risks out for each other by combining their network-buying power behind a single standard and common launch window. The success of the model came as a big surprise. Nobody wanted to be left out. Every mobile network operator in Europe ended up signing the MoU. But that was just the start. It swept GSM around the world to create a homogeneous global industry with its unique mix of cooperation and competition. Over the typical life cycle, a trillion dollars of investment feeds into the supply chain behind each new generation of mobile technology. On that scale the industry is not left predicting the mobile technology future – it makes it. Every research lab in the world is coupled into the same standards body and rapidly feeding back solutions to any technical glitch that emerges. Temple's model has been the basis of launching every new generation of cellular mobile technology since – "without a single failure".

The other major development that arose from Temple's GSM MoU was 'global' roaming. "It created quite an inspiring idea for travellers. You could land anywhere. You just switched your phone on, you did not have to do any registration or logging in. It just worked." And all of this was in a document that is just eight pages long. The result was that mobile phones had a far more successful global penetration than computers or the internet had achieved. "Coupling the two together has brought today's successful mobile computing revolution across the world."

WHAT COULD 5G DO?

Temple's second significant international intervention came later in his career, after he had retired. Again, the challenge was to sort out an international impasse, this time in radio spectrum for 5G. New generations of

SIMPLIFIED GUIDE TO CELLULAR MOBILE TECHNOLOGY GENERATIONS

Generation	Revolution in a word (or two)	Channel limit for data
1G	Cellular	25 kHz
2G (GSM)	Digital	200 kHz
3G	Multimedia	5 MHz
4G	Broadband	20 MHz
5G	Enhanced Broadband	100–200 MHz

mobile telecoms come along every decade or so. Every generation has its limits "baked in", Temple explains. "The whole idea of the technology generation change is to break those limitations and to be able to carry on expanding the market and capabilities."

Around 2012, people started thinking about what 5G would do. Temple believes that talks about that future spun in the wrong direction. He observed that the millimetre-wave components industry had quickly climbed on board, after hearing that 5G might use spectrum around 28 GHz. That would open up the billion-dollar market to them. "They more or less hijacked 5G." Between 2012 and 2015 everyone just assumed 5G would use 28 GHz. The entire focus was on an International Telecommunication Union conference in 2015 to turn it into a world-wide allocation. To everyone's shock, the conference decided the 28 GHz band was not going to be available in Europe for 5G. All that investment in the new technology and no bandwidth to roll it out in meant that the wheels had just fallen off the 5G bandwagon in Europe.

By then, Temple was a visiting professor in the 5G Innovation Centre (5GIC) at the University of Surrey. Unbeknown to Temple, Professor Rahim Tafazolli, the head of the 5GIC, was watching the 5G fiasco unfold. Call in Temple, was Tafazolli's suggestion. "He didn't ask me. He just said 'I've told the guys in Brussels that if anybody can sort this out you can'."

Once again, Temple was confronting a politically messy state of affairs. But where to begin? "I hadn't got a clue. I had been out of spectrum management for a great deal of time." Temple soon discovered that politics, spectrum and technology standards had become separated into watertight compartments. Talking about specific bands in the research community had also become frowned upon. "Because spectrum was bought and sold for billions, companies had regulatory affairs people in the mobile companies, whose job was focusing on specific spectrum bands." Temple's next 'little invention' came to the rescue. He asked himself how the research community could give itself a license to talk freely about specific spectrum bands. He cooked up something he called the '5G Pioneer Band'. His argument was "let's talk about the bands we would use for our research testbeds that would stand the best chance of being the same bands that would be rolled out commercially". That freed up conversations to talk about what commercially viable solutions might look like.

Temple said that 5G started in the wrong place in 2012. Everyone had embraced the assumption that 5G band would use 28 GHz before they had even looked at the problems 5G was setting out to solve. The 28 GHz spectrum band would provide massive data transfer rates for very nearby devices, but anything further away would be left in what Temple describes as "great valleys of darkness". The band was hopeless for covering wide areas. It would be taking out the great selling point of the personal smart phone – *using it anywhere*.

5G'S COMING OF AGE

Temple latched on to the fact that mobile operators weren't using just one band for their 4G networks to deliver both wide coverage and high capacity. Essentially two networks were being rolled out in parallel, one for coverage that was overlaid with another for capacity in high traffic areas. But 5G needed both coverage and capacity. This brought out the idea of finding a 'sweet spot' band that was the best mix of both attributes. Temple proposed to his European research collaborators that 5G in Europe in fact needed three bands: one purely for best coverage (700 MHz), one for maximum capacity to deal with super-hot spots of traffic (26 GHz) and the third at this 'sweet spot' that was identified at 3.6 GHz. It set Europe on an entirely different, and

A 4G small cell tower that is part of the University of Surrey 5G Test Bed

considerably better, direction of travel for its future 5G infrastructure.

That fundamental thinking was done by Temple in March 2016 and by September his idea of three '5G pioneer bands' had travelled through the various European bodies to finish up in Europe's 5G Action Plan being signed off at an EU Telecoms Council.

The industry may be shouting about its 5G services, but it's still early days for the technology. It isn't clear which application will take off. Some observers see 5G as the way to deliver Industry 4.0, or the fourth industrial revolution, joining up all parts of the manufacturing chain. So far, enhanced mobile broadband has been the first application to catch on. "That is the one that everybody is rolling out and it will take three to four years for its full impact to be felt," says Temple. "but the huge boost in capacity will come just in time for millions using data hungry applications." However Temple foresees trouble ahead on the coverage front. "There will be the most incredible digital divide across the country."

His view is that people will grow used to moving seamlessly between their fibre-connected homes and fibre-connected buildings. 5G will take up the slack as they travel between the two, but woe betide anyone stuck on an older generation. "When you move out of 5G coverage you really will fall off a cliff edge. And 4G networks are going to be really stressed out, because there just isn't the bandwidth." For Temple, the problem is that the regulator is not looking far enough ahead. They have settled on 2 Mb/s as being the "universal" data rate. Temple protests at that idea: "2 Mb per second! What is that going to look like 10 years from now?"

A MOBILE MUSEUM

Many people have an obsolete mobile phone or two sitting at the bottom of a desk drawer. Professor Stephen Temple started from there and says he "now has the most photographed mobile collection in the world". Not because of the collection but because his collection is on display at the 5GIC at the University of Surrey and "all the VIPs stand in front of it when they are photographed!"

He started the collection after writing a book, *A political history of GSM*. To add some technical interest he included a piece on the 25 phones that changed the world. Finding he had several of them sitting in his desk drawer, Temple started on an auction treasure hunt to find the phones from the story. However, the story was expanding faster than he could find the phones so he split it into technology milestones and great industrial designs.

Temple reels though some of the phones on display and their role in the development of the industry. There is the world's first camera phone, the Sharp J-SH04. Sharp had a hard time trying to persuade the Japanese mobile operators to take the idea seriously because the they didn't see the point of a poor-quality camera on a mobile phone. Eventually the smallest operator, J-Phone, ordered a batch of 10,000 phones, with only 2,000 with a camera. Temple finds it amusing that when he visited J-Phone two years later, many of the 8,000 camera-free handsets were still sat in a warehouse, unsold. The 2,000 camera phones had sold out almost immediately.

Between 2000 and 2007, there was a golden age of great design. Temple's collection contains a lipstick phone, a powder compact, a chocolate bar, and one that looked like a melted strawberry. The innovations in handsets didn't all come from industry giants. Take Technophone: a small UK company that came up with the first mobile telephone that you could put in a pocket, admittedly a large one. Another museum piece is the Hagenuk device with the first game on a mobile phone. The company was also the first to have an internal aerial as opposed to an external aerial. Then there was the small Norwegian company that came up with the 'swipe' idea several years before Apple introduced it in their industry game-changer, the iPhone. It was announced recently that one of the most popular industrial designs, the Motorola Razr, is making a come-back this year, complete with a folding screen.

Stephen in front of his mobile collection at the University of Surrey's 5G Innovation Centre

"This is where I sense that we should be doing something now for a problem that is going to hit us in five to seven years' time. The 5G regulatory framework is still not right." Temple isn't sitting back and awaiting developments. Inspired by the Department for Digital, Culture, Media and Sport's market expansion model (set out in the government's *Future Telecommunications Infrastructure Review*), in which new players are helped to provide 5G coverage in the gaps left by the mobile operators through giving them low cost access to spectrum, he recently took on the task of chairing a spectrum policy forum group on how to share mobile spectrum.

Temple believes that he still has one unique experience to offer the new generation of engineers coming into the radio spectrum field. "One of the things that makes spectrum management so complicated is that there are layers and layers of legacy. I can see work that I did in 1971 is still there." There can't be many engineers whose current activities can draw on their own work from nearly half a century ago.

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, **1944**. Apprenticeship at Marconi, **1961**. MSc in Electronics, University of Southampton, **1966**. Deputy Director, Home Office Directorate of Telecommunications, **1979**. GSM Memorandum of Understanding signed, **1987**. Visiting Professor, University of Surrey, **2013**. Fellow of the Royal Academy of Engineering, **2014**.

AN IMMUNE SYSTEM FOR COMPUTERS

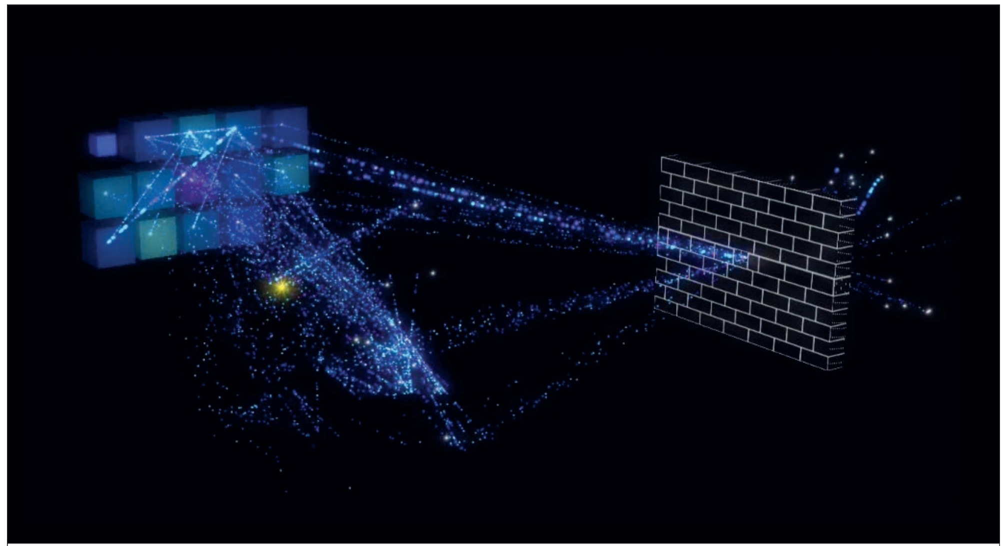
Darktrace has developed AI software designed to detect and defend against cyber threats from within computer networks – an immune system for computers.

Darktrace was established by Poppy Gustafsson and Jack Stockdale in 2013 when cyber intelligence experts from the US and the UK teamed up with mathematicians from the University of Cambridge. The resulting company was established to find new ways of protecting computer systems from malicious attacks. Its technology has gone on to be used by over 3,000 organisations of all sizes and scale, including Prudential, Suzuki and the US Department of Homeland Security.

Traditionally, cybersecurity relied on historical data of detectable signatures and rules, to spot and block threats. However, novel malware would not have a track record and could enter computer systems undetected. Darktrace counters this legacy approach by using artificial intelligence to create a self-learning cyber immune system. This defends all types of networks, including physical, cloud and virtual environments, the Internet of Things and industrial control systems.

Darktrace can be deployed on a company's network within minutes and uses Bayesian algorithms to apply probabilistic statistical reasoning to cybersecurity. The technology learns the normal 'pattern of life' of every user and device on a network, flagging suspicious activity with a percentage score of how likely it is to be a genuine threat. It provides an evolving cyber immune system that knows the usual activities of the organisation it sits within, meaning it can detect and, where necessary, contain the threat while enabling the system to continue running.

Darktrace's Cyber AI platform is powered by unsupervised machine learning, and was the first software of its type. The engineering challenge faced was in both speed and scale of analysis. Up to 100 million packets per second (a measure of throughput for network devices including bridges, routers and switches) needed to be analysed in real time to be effective.



Threat visualiser subnet view. One of the strengths of Darktrace is to present a simple interface that can then be drilled down upon so that the users know when to take action © Darktrace

Darktrace's Autonomous Response Antigena technology launched in 2016, providing – for the first time in the industry – the possibility of a 'self-healing' network. The technology works by harnessing the power and precision of Darktrace's threat detection, to calculate an effective but proportionate response to an in-progress attack. Once the AI has identified threatening activity that reaches a certain threshold of severity, its algorithms generate a real-time action that enforces the 'pattern of life' of the device or user affected, protecting the system from an emerging threat. This might involve interrupting specific, suspicious connections, automatically reconfiguring a part of the network or temporarily freezing certain user privileges. These reactions only target the threatening behaviour, so business elsewhere on the system can continue as usual.

Antigena was a MacRobert Award finalist in 2019, following the Enterprise Immune System's success in reaching the last three contenders in 2017. The company has seen huge take-up since it acquired its first client Drax, the electrical power generation company. Darktrace's technology is now being used by over 3,000 organisations across 110 countries, including the digital estates of government agencies, international banks, healthcare providers and telecoms operators.

Darktrace's rapid growth over six years has seen its valuation rise to over $1.65 billion, with offices in 44 countries employing over one thousand people.

For more information see: **www.darktrace.com**

HOW DOES THAT WORK?

GLOBAL POSITIONING SYSTEM

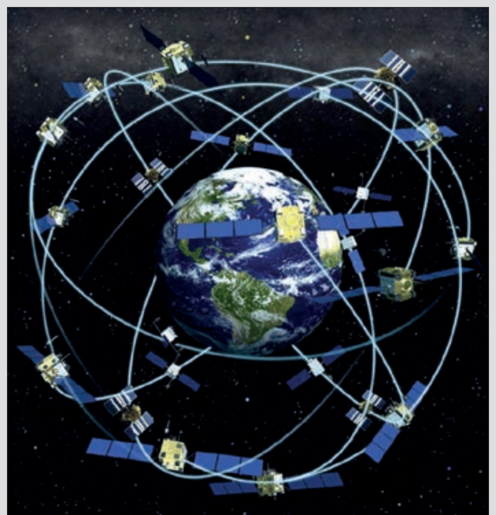
Billions of people around the world rely on a huge engineering infrastructure that extends across the planet and into space.

The global positioning system (GPS) enables anyone with a smartphone or navigation units on cars to pinpoint exactly where they are on Earth, as well as the precise time. It is also used in applications that range from aviation safety and banking to locating and rescuing ships in distress.

The American GPS, started by the US Department of Defense in 1973 as the world's first global satellite radio navigation system – helped make this possible. It was originally developed for military applications for positioning, navigation and timing services; civilian GPS is now freely available for peaceful commercial and scientific use.

GPS consists of a satellite constellation, a ground control network and user equipment or receivers. It can support a network of 31 operational satellites flying in Medium Earth Orbit at around 12,550 miles above the planet's surface. The baseline number of satellites used, however, is 24, with 12 for each half of the globe. Each satellite makes a near circular orbit around the globe twice a day, equally spaced around the equator. This allows users from virtually any place on Earth to access the system.

Signals from at least four satellites, using a process called trilateration, are required for latitude, longitude, altitude and time. Each solar-powered satellite broadcasts on the same signal frequency and carries four



GPS satellites orbit the Earth in one of six orbital planes. They are inclined to the equator by about 55 degrees orbiting twice a day. Their set up is designed to ensure that at least four satellites are visible at least 15 degrees above the horizon at any given time anywhere in the world © NOAA

extremely accurate atomic clocks. It transmits both the spacecraft's position and its time signal. Distance = Speed x Time. So, a ground receiving device will calculate the distance between the receiver and the satellite. It knows that the signal will travel at the speed of light and then will multiply this by the exact time taken, to work out the location on the ground to within a few metres, and, if on a moving vehicle, estimate the velocity too.

It is worth noting that satellite's high-frequency, low-powered radio signals are weaker than those from a light bulb and travel by line of sight. They can pass through clouds, glass and plastic, but are blocked or deflected by solid objects such as mountains or buildings and can be slowed by atmospheric conditions. Differential GPS can improve accuracy by computing corrections to the code-based distance range.

The US Air Force (USAF) manages the constellation and each satellite is in one of six orbits enabling it to provide continuous worldwide coverage. Twenty-four satellites were launched between 1978 and 1994 and, because the satellites have a lifespan of 7.5 to 11 years, next-generation satellites began launching from 2005 onwards.

The satellites are tracked by six USAF monitor stations around the world and there are two caesium atomic clocks in each station, referenced to GPS system time. GPS provides a standard positioning service (SPS) for civilian use and a precise positioning service (PPS) primarily for military use.

In recognition of their work on developing GPS, the Queen Elizabeth Prize for Engineering 2019 was awarded to four of the engineers involved in progressing the project during the 1970s and 1980s – see **www.qeprize.org**

Galileo, the European global navigation satellite system (GNSS), is due to become fully operational in 2020. This alternative system will operate from 24 satellites placed in three orbital planes and has a real-time positional accuracy to within a metre.