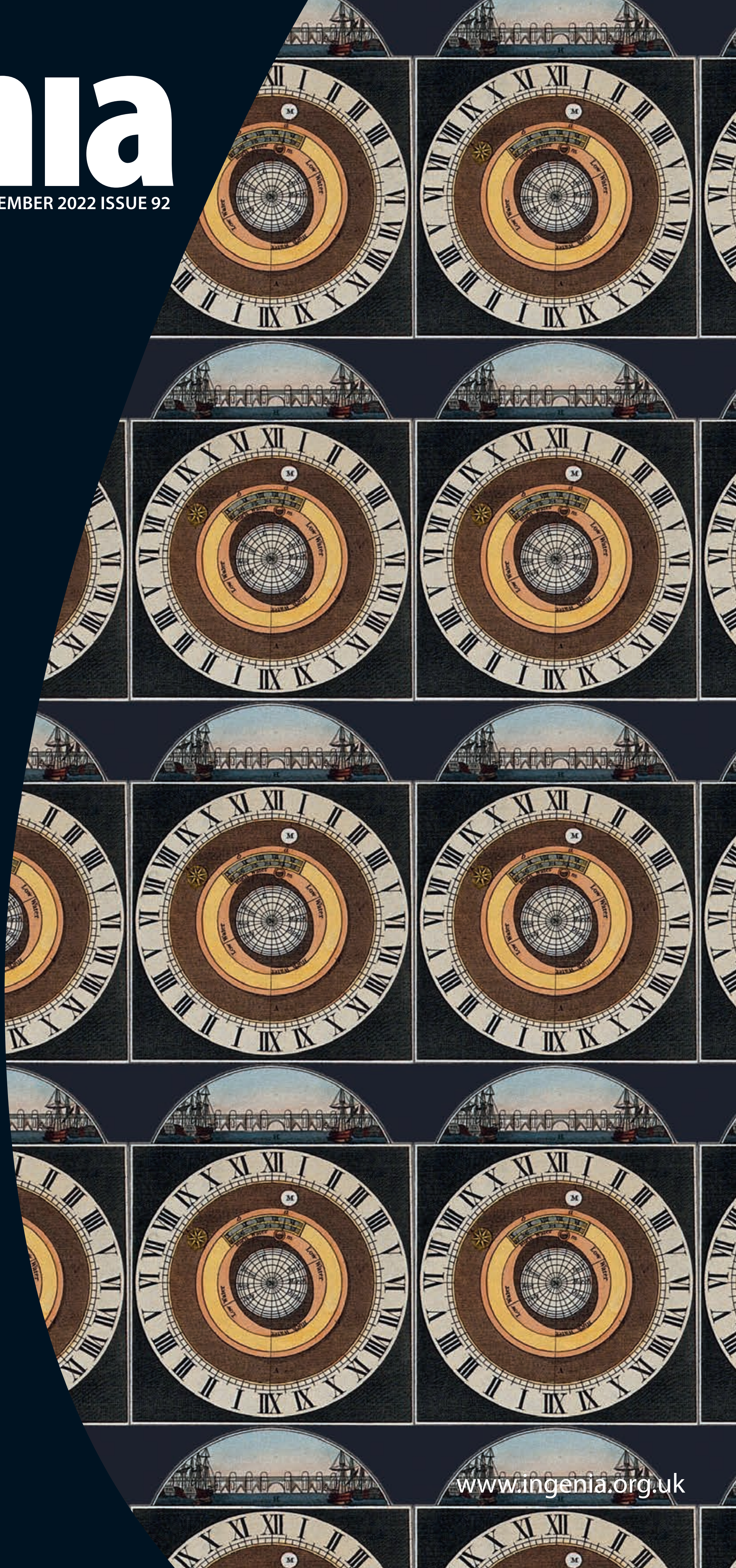
ingenia

SEPTEMBER 2022 ISSUE 92

A NEW KIND OF FOOTBRIDGE
A SUPER-SIZED ZOETROPE
RECREATING WORKS OF ART
ENGINEERING TOILET ROLL
THE IMPORTANCE OF PRECISE TIME



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Front cover

Coloured engraving of a Ferguson clock face, a 24-hour clock that indicates high and low tides and the phases of the moon. Coloured engraving by J. Pass, 1809.
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WELCOME

Engineers are inquisitive by nature – curious about all the things around us that we often take for granted. Finding out how things work leads to improved processes, making them more efficient, cost effective and more sustainable. From how we measure time (page 10), to how we manufacture toilet paper (page 26), engineers never stop improving our world.

In this month's Innovation Watch (page 42), Dr Kit Windows-Yule is using a groundbreaking technique to image and analyse the breaking down of plastic molecules in extreme heat – and through solid steel as well – to improve the system and enhance its role in the fight against plastic waste.

Similarly, a desire to improve his local playground led to Stan Jones (How I got here, page 6) becoming an adventure playground engineer, working with communities and children to design eco-friendly playgrounds that enhance the local environment.

Meanwhile, Madrid-based Factum Arte's use of cutting-edge technologies is discovering the secrets of centuries old artworks and manuscripts and recording them digitally so that they can be recreated if lost, stolen or destroyed.

And almost everything around us is underpinned by precise timing, from maps and banking to apps and emergency services. Dr Leon Lobo from the National Physical Laboratory describes how it works, what can happen if it goes wrong, and shares a new programme underway to make timing systems more resilient in the future.

To stay up to date on the work of engineers across a wide range of industries – sign up to our e-newsletter for more regular *Ingenia* content. Finally, please do keep telling us your thoughts on the magazine if you haven't already by contacting ingenia@raeng.org.uk or via #IngeniaMag on Twitter.

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

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UP FRONT

FEATURES

IN BRIEF

KIDNEY DIALYSIS MACHINE WINS MACROBERT AWARD

SC+ user Kuljit at home with her daughter © Richard Booth for Quanta Dialysis Technologies

HRH The Princess Royal speaks with award winners George Imafidon, Dr Mark McBride-Wright and Dr Robert Hammond

In July, the Royal Academy of Engineering hosted its annual Awards Dinner to celebrate engineers at all stages of their careers and recognise outstanding achievements and innovations from the UK's engineering community.

The highlight of the evening was the presentation of the 2022 MacRobert Award – the UK's most prestigious award for innovation in UK engineering – to the team behind a revolutionary compact dialysis machine that allows kidney failure patients to undergo dialysis at home, relieving pressure on overstretched hospitals.

With Quanta Dialysis Technologies' portable, easy-to-use SC+ system, patients can treat themselves at home overnight ('Kidney dialysis', *Ingenia* 62). With the device, they receive more dialysis care than they would in clinical settings and no longer have to go without dialysis over a weekend. Quanta is already working with NHS Trusts, and during lockdown provided its entire UK SC+ system stock to the NHS to relieve pressure on hospitals and ICUs. HRH The Princess Royal, the Academy's Royal Fellow, and Academy President Professor Sir Jim McDonald FREng FRSE presented the winning team with a gold medal and £50,000.

The other two finalists were vertical farming startup Intelligent Growth Solutions and Oxford Instruments, which has developed a transformative electron scanning microscopy tool.

The Princess Royal Silver Medals were awarded to five of the UK's leading engineering innovators. Read about the winners and their inventions, from advanced batteries to electronic skin, on page 34.

Equal Engineers Founder and InterEngineering Chair and Co-Founder, Dr Mark McBride-Wright received the Rooke Award for the public promotion of engineering, in recognition of his efforts to embed diversity and inclusion and rapid cultural change in engineering and technology.

The President's Medal, which is awarded to an Academy Fellow who has contributed significantly to the organisation's aims and work, was presented to Professor Dame Helen Atkinson DBE FREng. Dame Helen received the medal in recognition of her contribution to the Academy's work in education and careers outreach, including oversight of the *This is Engineering* campaign.

Meanwhile, the world's longest subsea interconnector, which allows renewable energy to flow between the UK and Norway, has won our renamed Major Project Award for Sustainability. Delivered in partnership between the National Grid and Statnett, the North Sea Link Interconnector Project aims to reduce carbon emissions by an estimated 23 million tonnes in the UK alone by 2030. Read a Q&A on ingenia.org.uk with team member and development engineer, Jennifer McCartney.

And five outstanding early-career engineers have won the 2022 RAEng Engineers Trust Young Engineer of the Year award. The recipients included Dr Robert Hammond, Industry Fellow at the University of St Andrews; Dr Matthew Marson, Global Market Sector Director of Technology at Arcadis; Dr Fragkoulis Kanavaris, Concrete Materials Lead at Arup; and Dr Beatriz Mingo, Research Fellow at the University of Manchester. The overall winner, George Imafidon, a pioneering Extreme-E performance engineer and social mobility advocate, also received the Sir George Macfarlane Medal. You can read all about George's route into engineering at **www.ingenia.org.uk/george-imafidon**

STUDENT TEAM WINS MOTOR RACING COMPETITION

A team of engineering students from the University of Glasgow won the Formula Student 2022 racing car competition, beating off fierce competition at an event held at Silverstone Race Circuit in July – one of the largest student motorsport competitions in Europe.

The Glasgow team is the first Scottish team to win the competition and the third British winner, following hot on the heels of 2021 winners, the University of Sheffield, and Cardiff University in 2017.

The competition, which is run by the Institution of Mechanical Engineers, gives students a real-world challenge to design, build and race single seater cars. These culminate in the finals event held at Silverstone, which combine formal presentations of their work throughout the year with a range of on-track events that demonstrate the capabilities of their car.

This year, there were also record numbers of participants in the autonomous car event, which was won by a team from the University of Edinburgh. Teams from the UK and overseas took part in presentations of their work and on-track activities designed to test their team's autonomous driving systems across several real-world driving simulations.

Find out more about the event and winning design, by visiting *Ingenia* online, where Glasgow Racing Team Principal, Jamie Clarke, has written a blog about the team's competition, at **www.ingenia.org.uk/winning-formula-student**

The University of Glasgow racing team's winning internal combustion engine vehicle at Silverstone during the competition in July 2022

HUMAN-POWERED SUBMARINE RACE CELEBRATES 10 YEARS

A team of engineering students from Rhein-Waal University of Applied Sciences, Germany, has won the 10th anniversary European International Submarine Race (eISR).

Held in Europe's largest freshwater tank, QinetiQ's Ocean Basin at Haslar Marine Technology Park over two weeks, the eISR asks teams to design, build and race underwater vehicles propelled by pedal power, that must navigate a challenging underwater slalom ('Racing human-powered submarines', *Ingenia* 72). Teams receive points for speed, manoeuvrability, reliability, and perseverance. Their ability to rise to the unexpected challenges of the underwater environment is especially important to their scoring.

Institute of Marine Engineering, Science and Technology (IMarEST) Race Director, William Megill, says: "When the IMarEST and QinetiQ created the eISR, the goal was to provide university students with an opportunity to apply their classroom knowledge to the design and actual production of underwater machines. The practical experience they obtain in their preparation, the teamwork they demonstrate at the competition, and the reflection of their successes (and failures) afterwards, uniquely prepare them for exciting careers in the maritime sector. The proof is in the pudding: of the approximately 1,500 students who have taken part in the submarine races over the last 10 years, many are now in positions of significant responsibility at marine engineering companies in the UK and worldwide."

The University of Michigan's stingray submarine, which placed second in the competition

ROLLS-ROYCE TO BUILD CARBON CAPTURE TECHNOLOGY IN DERBY

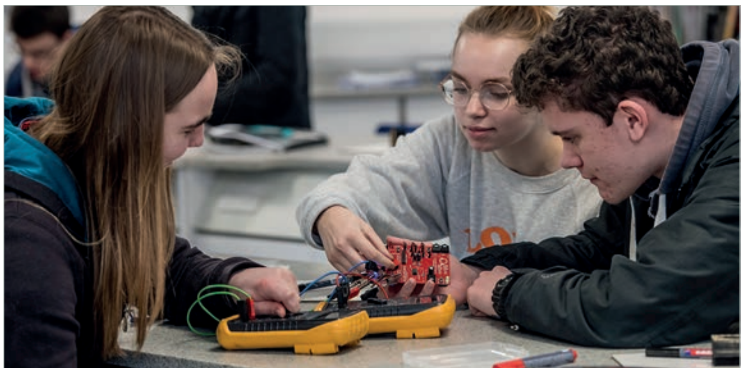
Rolls-Royce has secured £3 million from the UK government to build a demonstrator direct air capture (DAC) system, due to be operational in 2023. This carbon capture technology could play an important role in keeping global temperature rises to below 1.5°C by extracting CO_2 from the atmosphere.

In this type of DAC system, CO_2 is removed by passing air through a chemical solution. The rest of the air is then returned to the environment, while the captured carbon can be recycled to make fuel for the sectors that are hardest to decarbonise, like aviation. The system will be built and operated at an existing facility in Derby, which was previously used for testing jet engines. While the demonstrator will be able to remove 100 tonnes of CO_2 per year, a full-scale version of this plant could remove one million tonnes of CO_2 every year.

Jess Poole, Direct Air Capture Lead at Rolls-Royce, says: "Together the system works like a giant lung, sucking in air, absorbing the CO_2, and releasing what is not wanted. We use a water-based liquid to wash around 50% of the CO_2 from the captured air. Our technology is distinctive because very little water is used, and the liquid is recycled at low temperatures, making it energy efficient. Other technologies consume a lot of water and require substantial amounts of energy to generate heat for the separation of the CO_2."

The funding for the demonstrator comes from the Net Zero Innovation Portfolio via the Department for Business, Energy and Industrial Strategy, which aims to help deliver on the government's 10 Point Plan for a Green Industrial Revolution. Rolls-Royce received initial Phase 1 funding of £250,000 in 2021, which allowed the company to design the demonstrator in partnership with the Commonwealth Scientific and Industrial Research Organisation.

GET INVOLVED IN ENGINEERING



ELECTRONICS EVERYWHERE

Interested in electronics but not sure where to start? Why not try the 'Electronics Everywhere' kits for A-level physics and computer science students. With these classroom resources, you can try some music mixing, work out Planck's constant and more. Schools can register their interest by contacting **electronics.everywhere@ukesf.org** or find out more at **www.ukesf.org/schools/electronics-everywhere**

NATIONAL ENGINEERING DAY

2 November 2022

This is Engineering Day will return on 2 November 2022 as National Engineering Day and will focus this year on showcasing how engineering improves lives. Whether it's a device that makes music tactile or a virus-busting vaccine, clothes that grow with you or a battery that makes any bike electric, the day will make visible the engineers and engineering delivering small improvements to people's day-to-day lives, as well as helping to tackle the big challenges of our time. If you'd like to get involved, please email **sarah.wright@raeng.org.uk**

TOMORROW'S ENGINEERS WEEK

7 to 11 November 2022

Keep an eye out for this exciting week of engineering events and interactive opportunities that will explore what modern engineering careers have to offer. Details of how you can take part in the week will be available soon on **www.teweek.org.uk**

THE BROMPTON

One book on *Ingenia's* reading list this autumn is *The Brompton*, the story of the iconic Brompton bicycle and the company that built it. Lightweight, compact and now electric, the Brompton bike is instantly recognisable with its clever folding design. The book delves into this feat of engineering and how a small company grew to become one of the biggest cycling brand names in the world.

TURN IT UP

21 October to 21 May
Science and Industry Museum, Manchester

Explore the technology and science of music and how it drives us to create, perform, feel, and share at this exciting new exhibition. In among many other exciting installations, you can discover the musical robot Haile that can improvise along with human musicians; or see the groundbreaking haptic gloves used by artists like Ariana Grande to control music-making software live on stage.
www.scienceandindustrymuseum.org.uk/whats-on/turn-it-up

BRITISH SCIENCE FESTIVAL

13 to 17 September 2022
De Montfort University, Leicester

There's plenty to get stuck into at this year's edition of the British Science Festival, from immersive installations to scientists on stilts. Explore the hidden world of the scientific laboratory, witness the hidden cosmos with some of the first images from the James Webb Space Telescope or marvel at a projection-mapped spectacle of story, sound and light.
britishsciencefestival.org

NEW SCIENTIST LIVE

7 to 9 October 2022
ExCeL London

There's no shortage of talks and exhibitions to get engrossed in at this year's New Scientist Live. In the talks, hear about what gives humans the edge in the world increasingly populated by artificial intelligence and robots or let Sir Patrick Vallance FRS FMedSci walk you through the future of UK science. Meanwhile, among the exhibits are a pop-up planetarium, and the latest agricultural technology that's soon to play a vital role in tackling climate change. **live.newscientist.com/whats-on**

THE BIG BOUNCE

29 and 30 October
Glasgow East End

The physics festival and celebration of curiosity and innovation will return to the Barrowland Ballroom and other community venues in the East End of Glasgow in October 2022, with all events free of charge. Watch a snapshot of the 2021 festival at **www.iop.org/explore-physics/big-bounce-2022**

LIGHT UP THE NORTH

13 October to 11 December
Leeds, Blackpool, Lancaster, Durham, and Salford

See magical light installations in five different northern cities designed by local and international artists, that has in the past used technologies ranging from robotics to holographic projections.

HOW I GOT HERE

Q&A
STAN JONES
PLAYGROUND ENGINEER

Stan Jones has been working with Adventure Playground Engineers (APES) since he was at school, and is now a project manager leading his own design and engineering projects.

WHY DID YOU FIRST BECOME INTERESTED IN SCIENCE/ ENGINEERING?

I can't remember when I first became interested in engineering. I've always loved making stuff and being practically minded. As a child my house was always being renovated so I was accustomed to construction processes such as timber framing, plastering, electrical work, and plumbing. For my 14th birthday I gave my parents a list of timber to get for me so that I could build my own workshop in the garden, complete with work benches and some tools I'd saved up to buy. I mainly started with woodworking but over time my skills broadened, and I got into fixing electrical items such as electric scooters and I designed and built a disc sander. When I was 15, I started working at my local adventure playground doing all the structural repairs and general maintenance work. I couldn't believe you could get paid for fixing stuff!

HOW DID YOU GET TO WHERE YOU ARE NOW?

I got to where I am now through that very playground I started working at – St Pauls Adventure Playground. The playground had been burnt down and John O'Driscoll, the Founder and Director of APES, came to rebuild it (and make it better!). He spotted me doing some repairs and came to offer me a job alongside going to school. Working with APES, we dismantled the burnt structure and built in its place a huge treehouse that was eight metres from the ground with climbing nets and a climbing wall entrance. Since then, I've worked with them every minute I could, and was offered a place to leave school to live and work in London for APES, engineering playgrounds!

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

My biggest achievement would probably be being promoted to project manager at APES after two years and taking on my own design and engineering projects with a small team of engineers. I am proud to have been given that role and thankful to APES for providing it.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

My favourite thing about being an engineer is the problem-solving. I've always been in love with maths and so quick thinking and effective teamwork make me happy at work.

The 'Hertz So Good' soundsystem that Stan built for Shambala festival

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

I get up at about 6.00am, head to work for 8.00am, start at the workshop, and crack on with whatever project we have on at the time. Currently, we are fabricating 150 Gabion planters [sturdy metal basket filled with rocks] to make Parklets, miniature parks that provide spaces for people to interact, to rest, for children to play, for greenery, bike parking, and other community uses, in north west London. My role within the company is to designate jobs, ensure we have the required materials, employ quality control measures and, most importantly, keep everyone happy at work. APES' approach is to enhance the local environment by working with natural features and encompassing them in our designs. We encourage new planting, work to sustain local wildlife and either build around or incorporate existing trees into play structures without causing them harm. We also recycle and reuse all sorts of materials to give them new life in the playgrounds – including pianos! We also make sure to involve children and the local community in all our projects, so that they can have real ownership of the sites. I am also always happy to jump in and help out to get things done on time and efficiently!

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

Find an apprenticeship or first job where you can learn a lot from the people around you. Decide what you love about engineering and search to find that in a company.

WHAT'S NEXT FOR YOU?

My next project is to take over APES and become managing director! Just kidding! I just took my home-made sound system to Shambala festival to create a youth stage. I'm currently working on maintaining the sound system and adding parts to it. It's called 'Hertz So Good' and I designed and built it in my home workshop at the start of lockdown. It runs at about 11 kilowatts and is about

Stan working on a playground installation

2 metres by 2.5 metres at face dimensions. Then we've got a new playground to build in St John's Wood, London. It requires us to go down as a team and dismantle the existing rotten structures and put in its place brand new, thrilling ones.

QUICK-FIRE FACTS

Age: **18**

Qualifications: **GCSEs, AS maths, Engineering BTEC**

Biggest engineering inspiration: **Elon Musk**

Most-used technology: **carpentry/ fabrication**

Three words that describe you: **laid back, organised, and motivated**

OPINION

NEW STRATEGIES NEEDED FOR FLOOD RESILIENCE

News stories about extreme flooding are becoming a regular occurrence across the UK – every year, flash flooding is causing significant damage to homes and businesses, and even resulting in injury in some cases. Having chaired the Independent Expert Group looking into the London floods in July 2012, Mike Woolgar, Managing Director of Environmental and Water Management at Atkins, says that a strategic approach with support from all stakeholders is needed to make our cities more resilient to flooding.

It never rains. But it pours. This is misusing the proverb maybe, but it does feel appropriate, given recent weather. Recent weather means that we may, today, be worrying about water shortages, but the effects of climate change may be devastatingly felt in the form of flash flooding as high intensity rainstorms become more likely. As recently as early August, torrential rainfall after the dry weather caused flash flooding in parts of Devon, Cornwall, Somerset, and south Wales. Incidences of flooding have increased each year and it is now a regular pattern.

I recently chaired the Independent Expert Group (IEG) leading the London Flooding Review, which looked at the causes of the severe flooding in London in two days in July 2021. The flooding inundated hundreds of homes and businesses with water and sewage, and many residents are sadly still not back in their homes a year later. Rainfall overwhelmed the combined sewers, forcing sewage and water back up connecting pipes into dwellings and water was ejected from sewers that had reached capacity.

The IEG, which included Lykke Leonardsen, Head of Resilient and Sustainable City Solutions at the International Water Association, and Professor Roger Falconer FREng from Cardiff University – originator of many of the hydraulic models used for assessing flooding risk – sought information and anecdotes from the events to establish the best evidence and data set we could. Our investigation ran from early November 2021, supported by analysts and engineers from Mott MacDonald, and we issued our final report on findings and recommendations in July 2022.

It proved difficult to assemble all the necessary information. While we could access the Met Office rainfall radar data, Thames Water's current sewer models for the affected areas and data showing the state of the Thames during the events, we never managed to get a complete and reliable set of reports of flooded properties. The different methods used and timescales adopted by the various parties to collect and manage the data meant that information was not available when we needed it. We used data we received, supplemented by anecdotal and video evidence from residents and social media, and took account of new data that arrived over the course of the study.

Given the ‘thin’ data set, we made wide use of sensitivity testing – the impact of variables on uncertain data – to assess our findings’ robustness and used a broad-scale 2D model to show how water flowed around London at the surface. This enabled us to consider interaction between surface water and sewer systems.

One question from a resident particularly resonated. Badly shaken by the rapidity of the flooding she wanted to know whether the sewer system “had broken or wasn’t operated properly, which could be fixed” or whether the event was truly extreme; either way she might feel less scared of being flooded again.

Although return periods, which measure the likelihood of storms of this nature happening, vary for different areas and durations of rainfall, and each flooding event lasted different periods and covered separate areas, both were extreme with respect to current meteorological records: less than 1% Annual Exceedance Probability, meaning less than a one in 100 chance of happening in any year.

We also tested whether anything ‘was broken’, including pumping stations, flood alleviation schemes, road drainage gullies (grilles), sewer blockages, and the like, which could be fixed. Compared to the overwhelming amount of water that fell, none of the items we tested would have had a significant effect on the flooding levels – apart from tidal locking of sewers due to the state of the tide (where the level of the tide is sufficient to hold closed the flap valves through which the storm water flows to the river). An estimated 2.5 million m^3 of rain fell on 12 July in two hours. This volume cannot be held in underground sewers – which are generally designed for one-in-30-year events; compare that with the Tideway Tunnel, which at more than 30 kilometres long and with a 7.2 metre diameter can hold less than 1.6 million m^3.

Water in extreme events must be managed safely on the surface; keeping excess water out of sewers reduces both the risk of sewage getting into properties and of sewage flowing into the Thames. Managing water on the surface means that Local Authorities (LA) – responsible as land planners and Lead Local Flood Authorities – have a significant role to play.

Large numbers of properties are at risk of flash flooding. Over decades more houses and impermeable areas such as car parks, paved areas and conservatories have been built, increasing both the amount of potential runoff and the numbers of houses at risk of flooding. Many people live in basements in London and here lives are at risk. Climate change may make this worse, so action is required to reduce risk for current and future residents and businesses. Without action, future flooding losses may not be covered by insurance, with severe social and economic impacts.

Water obeys topography and not administrative boundaries. We showed that even completely unblocked road gullies could not accept the surface flows that occurred, meaning water flowed downhill often from one LA area to another until it could enter a sewer or a house. A strategic approach is needed where LAs cooperate in the design, development, and management of surface water schemes.

Data, along with system modelling and land use policy, should be common and shared. Long-term prioritisation of schemes to offer the greatest benefit can then be undertaken and, with strategic oversight, multiple parties including LAs, water companies, developers, and other landowners may be brought together to be accountable for their obligations and provide more effective solutions to hold back the flow.

The Mayor of London has convened a Surface Water Management Strategy Group – a great step forward – to offer strategic oversight. Governance is being developed and this needs all of our support as governance allows funding to flow.

The Regional Flood and Coastal Committee has significant funds available for surface water management and wants larger strategic schemes brought forward to maximise effectiveness. A strategic approach would be welcomed.

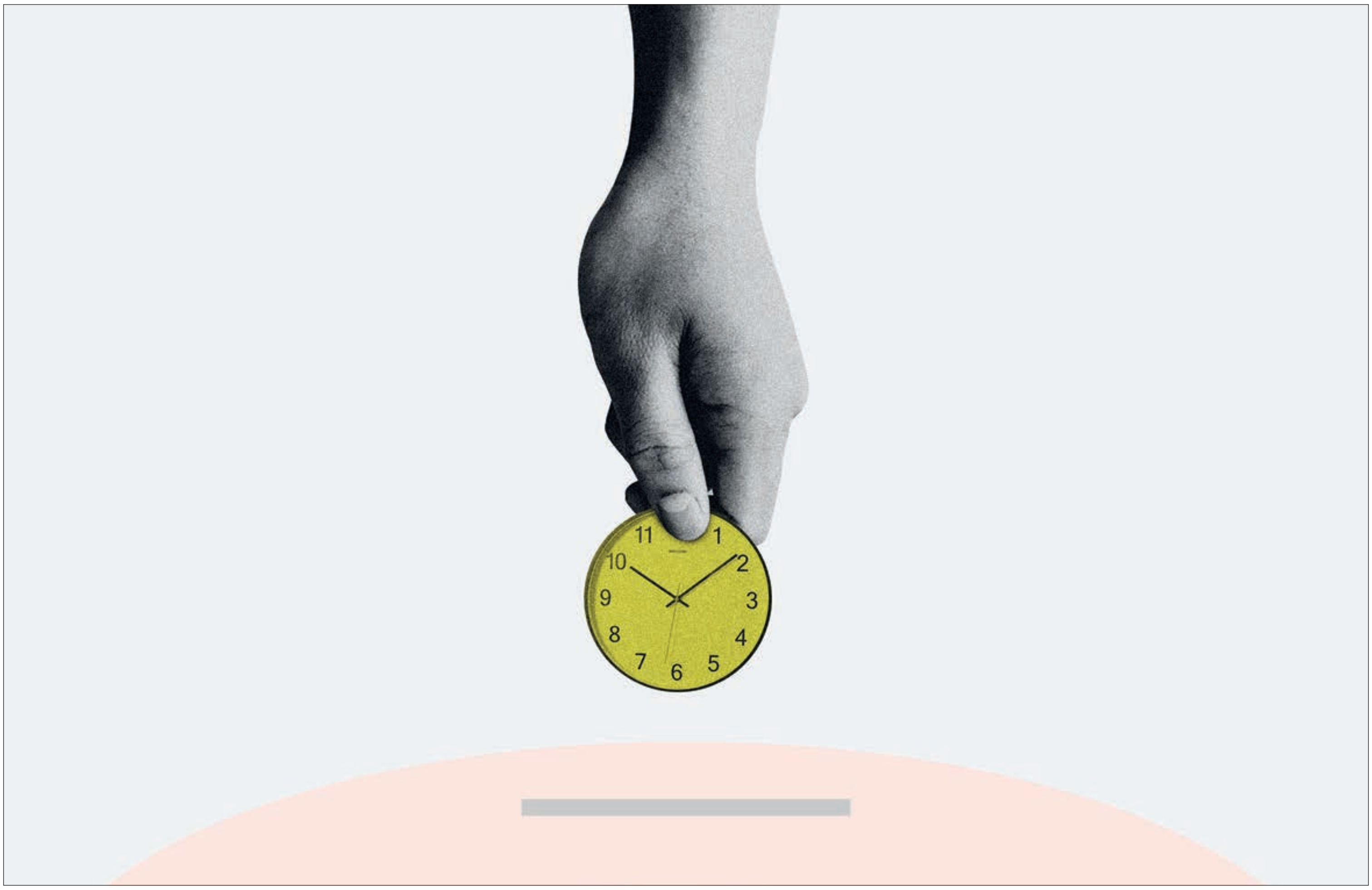
Copenhagen’s experience, which put in place a climate change adaptation plan for urban flooding following extreme floods in 2011, shows safely managing this sort of event takes time, resolve, and significant investment. We must start the process now, dealing with current institutional obstacles and strategically directing flows of funding to reduce flows of water, or find ourselves in an ever-worsening and more difficult situation to reverse.

While this work proceeds, residents, particularly those in at-risk basements, need information and support to help understand and manage their situations. Engineers understand the impact of climate change on urban flooding, so the profession is in the ideal place to provide long-term solutions to address these challenges.

BIOGRAPHY

Mike Woolgar has over 40 years’ experience in the water sector in the UK and internationally. His working life has been spent in the water, urban development, flood management, irrigation, and renewable energy sectors. In the UK he has worked on regulation, policy, advisory services, due diligence and expert services, and infrastructure project preparation in the regulated utilities, flood risk management, and resources sectors. He has extensive experience of infrastructure development including regulated and private sector water and waste systems, water resource planning, water systems development engineering, climate change, and sustainable energy.

To read the London Flood Review report in full, please visit ***www.londonfloodreview.co.uk***

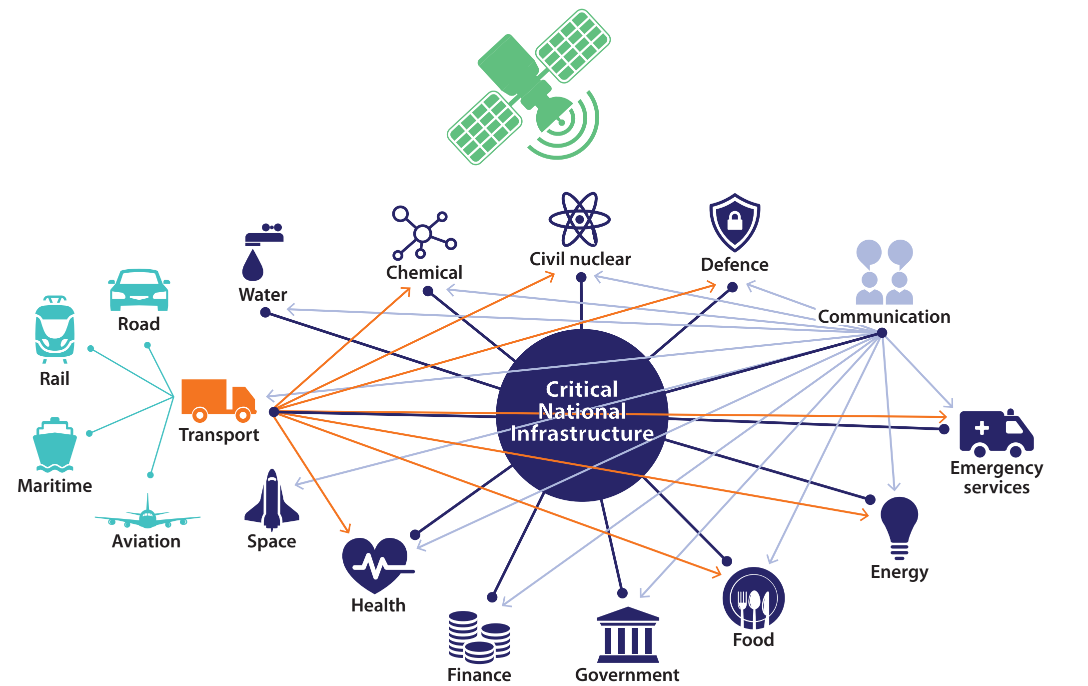


WHY MICROSECONDS MATTER

Without precise timing, we'd be lost – and not just literally. Along with guiding our maps, timing underpins everything from ridesharing apps to bank transactions, to the emergency services and the flux of energy from the grid to our homes. Dr Leon Lobo, Head of the National Timing Centre at the National Physical Laboratory, discusses super-precise time, how it is coordinated across the world, and what can happen if it goes wrong. He also shares how the UK is making time more robust for the future.

Did you know?

- Much of our digital infrastructure, from navigation apps to banking transactions, relies on the ability to accurately measure time down to the microsecond or even nanosecond
- Most timing signals come from weak satellite signals from space, which can be vulnerable to interference
- Failures in these satellite signals could cause losses amounting to billions of pounds to the UK's economy, so the government is developing alternative approaches to make timing more robust



Critical national infrastructure describes the resources, systems, processes, and facilities that keep society and the economy functioning, from generating electricity and transmitting it around the country, to producing and transporting food in agricultural supply chains. The communications networks and transport systems that underpin so many other sectors are heavily reliant on GNSS (adapted from a diagram provided by the National Physical Laboratory)

You wake up in the morning as your alarm on your smartphone goes off, synchronised to your wake-up time by a network of satellites ('Supercharging GPS precision', *Ingenia* 90) overhead. The very same technology tracks your location on your morning run. You boil the kettle to make a cup of tea with electricity from the grid – which is itself synchronised by satellite-based timing. On the platform at the train station, you see on the overhead signs that the train is delayed by one minute, thanks to coordination of its GPS location with your local station.

We unknowingly reap the benefits of technologies that can precisely detect time and location numerous times a day, every day. Even just on our smartphones, we have a direct line to this invisible yet integral utility that underpins much of the infrastructure and systems that keep the world turning. It has been estimated that satellite-based positioning, navigation and timing services – the global navigation satellite systems (GNSS), such as GPS – directly support over £250 billion (13.4%) of the UK economy. As a result, a breach or failure in GNSS can cause all manner of problems with services we rely on, not to mention potentially costing the UK economy over £1 billion a day.

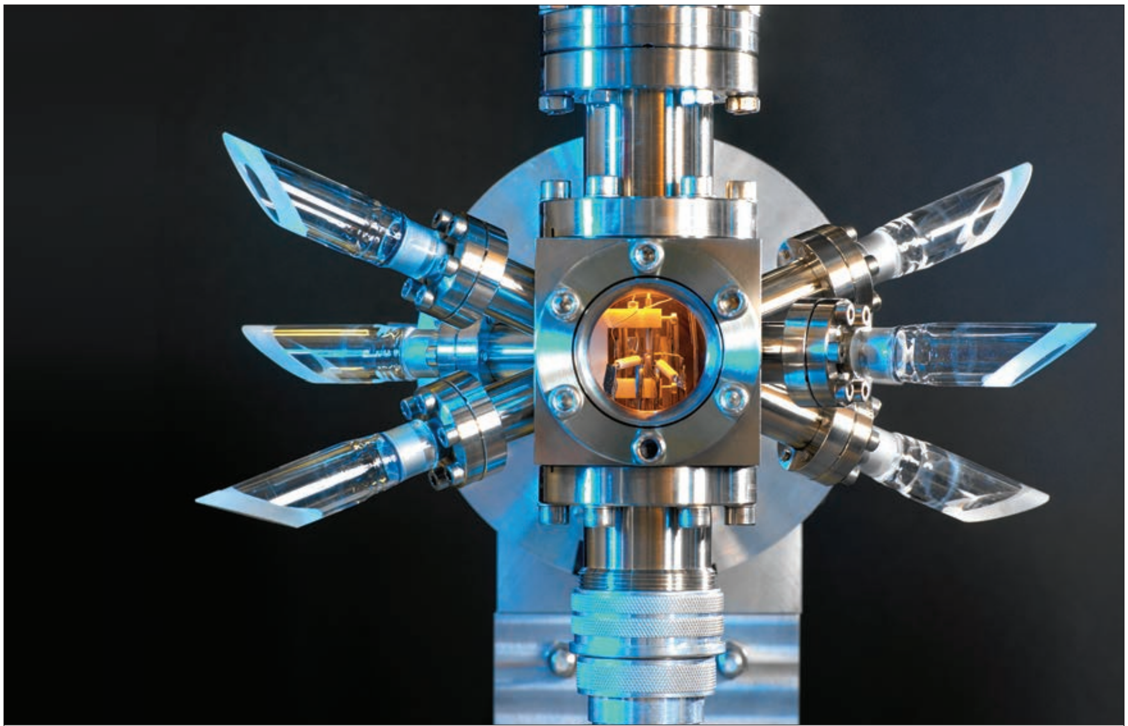
We have come to rely so deeply on these technologies that the resilience in the provision of timing is now a challenge.

MEASURING TIME WITH ATOMS

A few thousand years ago time was simply measured by light and dark and the movement of astronomical bodies across the sky – all you needed to know was when to get up to labour in the fields and when to stop and go to bed.

Before clocks as we know them came along, humans devised ingenious methods to measure the passing of time, from falling sand in an hourglass, the slow burning of incense, or the flow of water between vessels. Water clocks became increasingly sophisticated in 11th-century China and the medieval Islamic world, with geared mechanical systems displaying different mannequins on the hour.

Whether for religious prayer or widening webs of commerce, as societies became more interlinked and synchronised across geographies, timekeeping became increasingly sophisticated. Between the 15th and 20th centuries, the world saw the development of striking clocks in bell towers, spring-based watches, much more accurate pendulum clocks, and electric and quartz oscillator clocks. In



The next generation of atomic clocks at the National Physical Laboratory, using laser-cooled trapped ions or atoms, should achieve accuracies about 100 times better – equivalent to gaining or losing no more than one second in the age of the universe © National Physical Laboratory

tandem came new learnings in science and technology: from measuring gravity and modelling the shape of the Earth, to locating ships at sea.

Two timing innovations, in particular, are cornerstones of the world today.

One is the quartz oscillator, invented at Bell Laboratories in 1927. Based on the electronic oscillations of a quartz crystal, it is used in the majority of the world's clocks, watches, computers, and devices such as kitchen timers. While more accurate than its predecessors, the frequency of oscillation depends on the temperature and dimensions of the crystal, so no two quartz clocks are the same. For most purposes, calibrating against another time reference – solar time, or the Earth's rotation period – was sufficient.

However, because of the Earth's fluctuating spin, solar time and the 'true' universal time gradually deviate from one another (which also causes strange side-effects, such as the leap second – see box-out). For scientists chasing this 'true' measurement of time, an alternative benchmark was needed.

In 1955, physicists at the UK's National Physical Laboratory (NPL) built an atomic clock based on counting energetic transitions in caesium atoms ('Compact atomic clocks', *Ingenia* 57). It quickly became apparent that atomic time was a much more stable and consistent benchmark than the Earth's rotation, which led to a new definition of the second in SI (Systeme Internationale) units in 1967. Today, the successors of these clocks sit in national laboratories the world over, from Teddington in the UK to Washington in the US, and are used to calculate the Coordinated Universal Time (UTC) standard time scale.

NPL has managed the UK's time scale for many decades at its site in Teddington. The time scale is based on a suite of hydrogen masers and caesium beam clocks, steered by caesium fountains that provide the realisation of the SI second.

UNIVERSAL TIME

Atomic clock data from about 75 timing laboratories around the world, such as NPL, is used to define UTC. All clock data is submitted to the Bureau of International Weights and Measures (BIPM) in France. Every month, UTC is computed as an average of all the data received and published in a report called *Circular T*.

The upshot is that most national time scales operate a few nanoseconds faster or slower than UTC. This drift can occur because of electronic or gravitational effects, for example, and can vary over the course of a year. Time scale laboratories can correct this drift, or 'offset', to UTC, in a process called 'steering'. This is usually done by shifting the frequency of the output – rather than the clock itself – with a device called a frequency offset generator. (Alternatively, the lab can accept the offset and inform their user community accordingly, who can then account for it within their own systems.)

One of the most important ways UTC is used is for GNSS

THE LEAP SECOND

In 1972, physicists introduced the leap second as a way to 'correct' UTC to solar time: meaning that every few years, one extra second has been added to the end of a day. Since then, 27 leap seconds have been applied to UTC. However, recently, technology companies such as Meta and Google have been arguing that the leap second should be phased out with an alternative, because it can cause computer programs to crash and, historically, outages on some of the world's most popular websites, including LinkedIn and Reddit. Moreover, in the last few years, the Earth has seen more than 30 of the shortest solar days since high-precision measurement of time began, with about a millisecond and a half shaved off each of them. If solar time continues to run faster than universal time for long enough, a negative leap second will be required. With as-yet unknown effects, it could cause even more chaos in the tech world than its positive counterpart.

TIMING IN GNSS SATELLITES

Position and time are obtained by a GNSS receiver using time-of-arrival measurements of timing signals from a minimum of four satellites. The fourth satellite is needed to determine the time offset between the receiver's internal clock and GNSS system time to measure 3D position coordinates and time. This enables the receiver to correct its internal clock, now steered to the signals from space, and effectively offer atomic clock timing capability. The use cases resulting from this invisible utility touch all areas of our daily life, from our morning alarm clock to our train journey home.

– see 'Supercharging GPS precision', in *Ingenia* 90 for more. While atomic clocks are found in orbit onboard GNSS satellites, the timing signals that they use are steered by clock facilities on the ground. The latter tend to be steered themselves to time scales managed at national facilities so that they remain close enough to UTC. For example, the GPS ground segment clocks at Shriever Air Force Base are steered to the UTC time signal from the US Naval Observatory in Washington DC. The result is that the time provided by GPS is within 40 nanoseconds of UTC.

KEEPING THE RADIO ON AND ELECTRICITY FLOWING

The importance of precise and accurate timing manifests in surprising ways. For example, the slightest timing anomaly can disrupt entire TV and radio networks. In January 2016, GPS receivers skipped by just 13 microseconds and caused disturbances across UK digital radio services for several hours. The same event also caused police and fire radio equipment in parts of North America to stop working.

From live sport to prime-time TV shows, broadcasting big events also depends on large audio and video data files synchronising between the filming venue and the processing studio to provide a harmonised audio-visual experience for viewers. Because large chunks of data are transferred separately, and recombined after transfer, the traceability of the time source is vital. Accurate time enables data integrity, analytics, governance, timestamping, and latency monitoring, for a seamless viewing experience.

Timing is also essential for the energy grids supplying homes and buildings with electricity. To balance electrical loads and avoid outages, grid operators must increase or decrease the electricity supply produced by generators. To do this, they need to know the currents at different locations, with very accurate timestamps. Phasor measurement units (PMUs) can be used to do this: they take real-time measurements of alternating current (AC) waveforms on the energy grid. They sample the AC waveform (at the microsecond level of accuracy) across sections of the grid and typically receive their time signals from GNSS systems. Many PMUs also have atomic clocks as a backup in case of GNSS outages.

Synchronisation and PMUs are starting to be used more widely as we get our energy from a wider variety of sources. Whether the source is a conventional power station, a wind farm, or consumers selling electricity back to the grid (for example if they have their own solar panels), a more intelligent grid will be key to a reliable supply. With the growing complexities of our energy supply and demand, PMUs could in future be used to help automate load balancing. However, this means the energy system could become vulnerable to GNSS outages unless alternative timing approaches are used.

TRADING AT (ALMOST) LIGHT SPEED

Accurate and traceable time also keeps the finance sector ticking along. Stocks and futures exchanges can take place in less than the time it takes to click a mouse – milliseconds or even nanoseconds for some high-frequency trades. High-frequency traders are in a 'race to zero': making transactions faster using every possible means. Every millisecond and microsecond is vital. For example, to communicate between different financial centres, microwave links, where data travels through the air, are preferable to optical fibres. In optical fibres, the information is coded in a light beam before travelling along a glass fibre, where it is slowed to two-thirds of the speed of light in a vacuum. (One emerging approach to better this involves hollow-core optical fibres, in which light has been shown to travel at 99.7% of its speed in a vacuum – see 'Hollowing out a future in fibre optics', *Ingenia* 79.)

At these speeds, it is vital that data on these transactions is correctly timestamped and synchronised to a universal reference time. Knowing precisely when every trade takes place is essential to properly regulate trading. For example, in a matter of minutes in 2010, Wall Street's Dow Jones index temporarily lost almost 9% of its value. Stock values dropped

SPOOFING AND JAMMING

Disruptive interference of GNSS signals can occur unintentionally or maliciously, with several instances of hostile state actors demonstrating this capability over the past few years. Potential interferences include jamming or denial of service, rebroadcasting a GNSS signal intentionally or accidentally, or spoofing GNSS signals to create a controllable misreporting of position or time. Jamming devices, for example, are easily available online, and can be used by car thieves to secretly prevent a driver from locking their door. However, many systems that rely on signals from GNSS have procedures in place to deal with any GNSS-based system faults, and some infrastructures use backup timing devices such as atomic clocks that offer business continuity for a duration before drifting out of specification.

A state-of-the-art NPL Instruments caesium primary frequency standard, next to its control and test electronics © National Physical Laboratory

by over $850 billion, although luckily, mostly recovered by the end of the day. Although there are different theories to explain this so-called 'Flash Crash', the lack of synchronised timestamping for transactions at the time meant that proper analysis is impossible, even now.

Market regulators have now wised up to this, with a 2018 European regulation, known as MiFiDII, setting much tighter requirements for timestamping trades. For human trading (such as over the phone or online), it states that accuracy must be within one second. For automated trades performed by algorithms, it states accuracy must be within one millisecond of UTC for electronic trading, and just 100 microseconds for high-frequency trading. Trading organisations face fines of up to five million euros, or 10% of global turnover, if they don't meet these standards. (Outside of Europe, the international finance regulator, IOSCO, has also put forward a recommendation for global markets to implement UTC-traceable timestamps for trading.)

To adhere to MiFiDII, GNSS is used for timestamping by many financial organisations. However, it can be spoofed or jammed (see box-out). It can also be vulnerable to poor signal or errors, such as that might result from a solar storm. One solution for this available to UK traders is NPL*Time*®. Accurate to a microsecond, its time signal – directly traceable to UTC – is delivered via a fibre-optic cable.

FORTIFYING OUR TIME SERVICES

As we have seen, much of our critical infrastructure relies on precise timing – and in particular, many of these pillars of society are dependent on GNSS. Interferences or outages could bring down these very pillars, with potentially life-threatening effects. This might mean preventing the emergency services from locating emergencies or sending a plane off its scheduled route and creating the potential for a collision. Clearly, there is a need for alternative technologies that can reduce our dependence on these weak signals from space. Furthermore, since the time scale delivered by NPL operates from a single site, it can be thought of as a single point of failure – if it breaks down, there is no backup.

The UK is making steps towards a more resilient national time scale by establishing the National Timing Centre (NTC) programme. During the five-year programme, a new geographically distributed national time scale will be developed by NPL and a UK-wide team of researchers, situated on several secure sites connected to one another. Rather than choosing only one method for transferring time and frequency signals between sites, resiliency will be achieved through diversity. What this means is using several different methods of transfer, such as fibre, satellite communications and even GNSS, each with very different failure modes. Known as the Resilient Enhanced Time Scale Infrastructure (RETSI), it will be a world first, and form the core of a systems-of-systems approach to national timing resiliency.

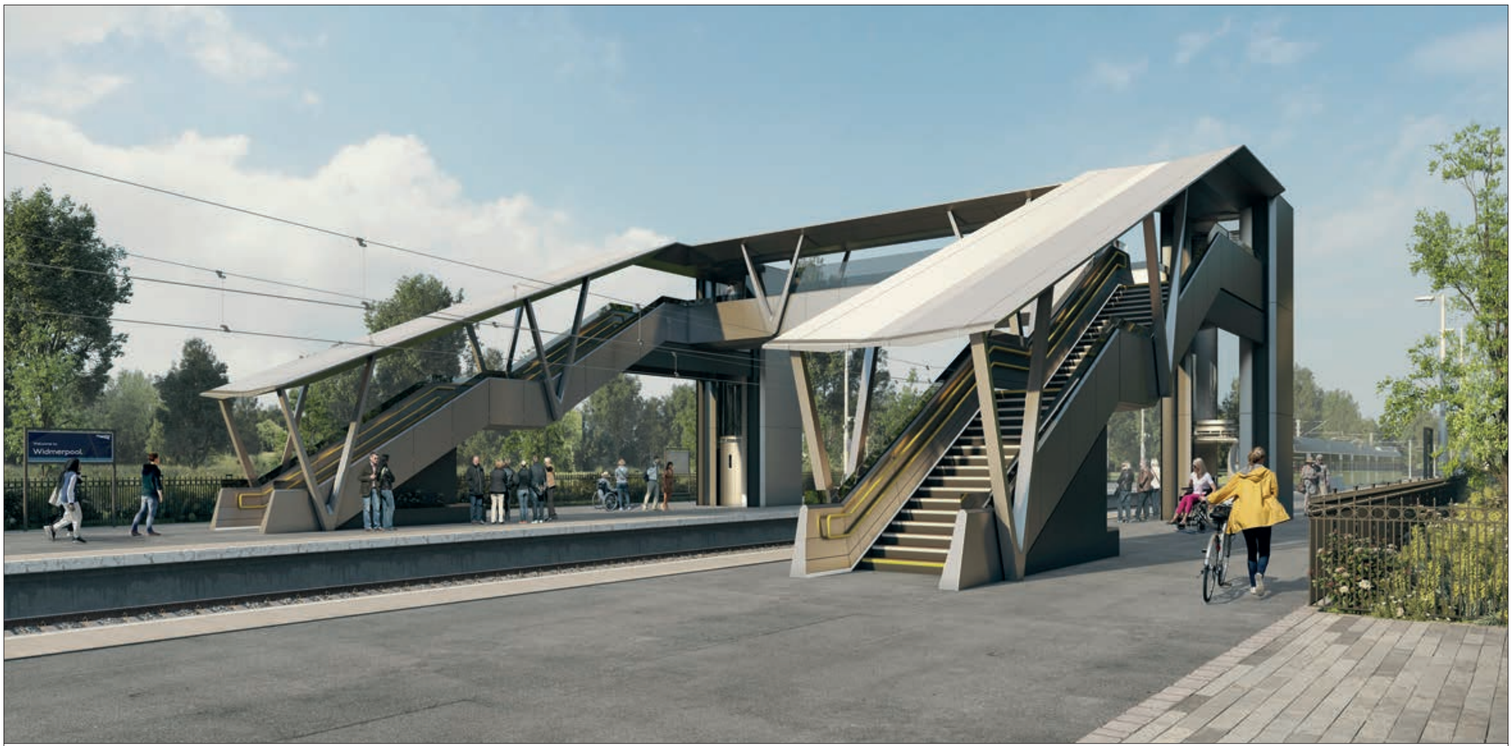
The NTC programme, rolling out systems over the next two years, aims to ensure split-second timing is available wherever it is needed, whether on our devices or in the energy, broadcast or finance industry. More resilient timing systems that are independent of GNSS will for one thing, enable faster, more secure internet. But even more importantly, they will help society weather solar storms and resist jamming, from the emergency services to the London Stock Exchange – making the potential havoc that we might see today a thing of the past.

BIOGRAPHY

Dr Leon Lobo is Head of the National Timing Centre (NTC) programme at NPL, focusing on developing and delivering a national timing strategy.

A 'FLAT-PACK' FOOTBRIDGE

The humble railway station footbridge is the focus of an imaginative initiative to bring the benefits of modern manufacturing techniques to the construction industry, which still tends to treat each new building or piece of infrastructure as a 'one-off'. Hugh Ferguson spoke to the engineers who took a fresh look at the footbridge's design and manufacture.



A render of how the AVA footbridge will look, in one of its configurations. The first 'demonstration' bridge will be installed later in 2022, and the first order has been placed for one at Stowmarket station in Suffolk for installation in autumn 2023 © Expedition Engineering

Although probably not given much thought by many ,the railway footbridge plays an important role at numerous train stations across the UK, allowing travellers to access their required platform and continue their journey. Yet, the design, manufacture and construction of these ordinary structures have changed little over the past century. And all have significant impact: basic railway footbridges cost £3 million to £4 million each, with more modern designs costing more; take a year or more on site to build; require multiple disruptive 'possessions' of the railway; and are expensive to maintain. With many also being in place for several decades, upgrades are needed for stations to become more accessible and greener.

To address these challenges, Network Rail brought together a consortium of firms that were relatively new to railway work (with one exception) and SMEs with specific expertise, with the reasoning that these kinds of companies would be more agile in developing and responding to new ideas.

The result is the modular design of the AVA footbridge,

Did you know?

- Railway station footbridges can cost more than £4 million each, take a year or more to build, installation closes railways multiple times, and they are expensive to maintain
- The design, manufacture and construction of these footbridges hasn't been updated in decades
- The new AVA footbridge can be manufactured and built off-site, then slotted together like a giant Meccano set when installed

Manufacturing the AVA Bridge (L–R): The computer screen shows a 3 metre by 1.5 metre steel sheet marked up multiple parts to be laser cut, using 92.9% of the sheet, resulting in less wastage and carbon emissions. The sheet is cut by the computer-controlled laser and then folded

which aims to revolutionise how footbridges are built, reducing time, cost and whole-life carbon emissions. It can be adjusted to fit any station anywhere.

FACTORY MANUFACTURE

The key aspects of the bridge's design are factory production and low maintenance. One of the new contractors, X-Treme Systems, a stainless steel fabricator, had particular expertise in manufacture from stainless steel sheets. This and its experience of constructing bespoke storage systems from cut and folded sheets neatly fitted the brief. The consortium chose stainless steel as the core material, which is expensive initially, but also rustproof, vandal proof and never needs repainting. Also, steel sheet can be laser cut, drilled and folded to almost any shape with tolerances as tight as 0.2 millimetres, by robotic machines controlled by fully integrated 3D software models that include every nut, bolt and plate.

The footbridge's structure is created from a standard 3 metre by 1.5 metre plate, which can be as thin as 6 millimetres. The designers were careful to maximise the use of each sheet to minimise waste, using software to match the number of parts to be cut from a standard sheet. Although about 5% of the bridge's joints have been welded (using high heat to melt the parts together, which then cool and fuse), the extreme accuracy of the machine-cut parts means that bolted connections are more appropriate and allow the whole bridge to be snapped together like a Meccano set. Elements are factory-connected into 1.2-metre-long modules, then taken to an assembly shop for connection into about nine units (including the bridge deck, stairs units, roof units and V-shaped roof supports) for transport to site.

Site preparation for the bridges normally avoids the disruptive and time-consuming 'wet trades', in this case mixing and using concrete, with the option of installing some grillages or screw pile anchorage systems. A relatively shallow lift well will need to be excavated, requiring less disruptive and expensive temporary works. The bridge parts can then be lifted into place and bolted together, and the precommissioned lifts attached [see 'The lift']. Initially, construction will require possession of the railway over

Modifications made following testing of the prototype resulted in the primary structure of a U-frame formed from two longitudinal girders, concealed within the parapet and linked by crossbeams. The main girders are made of 1.2 metre-long panels folded to make a C, with the top and bottom flanges strengthened by extra plates, and all elements bolted together to form a continuous structure. This allowed a continuous glass window to be provided above the parapet, improving the user experience. (The U-frame above is supported on an improvised construction trolley, made from recycled parts of the original prototype) © X-Treme Systems

The original partners in the AVA Bridge consortium were:

- Network Rail – which provided the £5.4 million funding, supported by Transport Infrastructure Efficiency Strategy (TIES) Living Lab, a collaboration of 25 partners together with government, the Infrastructure Industry Innovation Partnership (i3P), and the Construction Innovation Hub, funded via a grant from Innovate UK, and contributions from the Department for Transport, HS2, Transport for London, Network Rail, and Highways England
- Walker Construction – an experienced railway contractor
- Expedition Engineering – lead designer
- X-Treme Systems – steel manufacturer with no previous experience of bridges
- Manufacturing Technology Centre.

The consortium worked in collaboration with Hawkins\Brown, Atelier Ten, the Norman Foster Foundation, SCX Special Projects, and Quantum Infrastructure.
The revised consortium going forward for delivering AVA Bridges comprises Walker Construction, Expedition Engineering, Hawkins\Brown, X-Treme Systems, and SCX Special Projects.

THE LIFT

Very early on, the Expedition team identified a major deficiency in the initial brief: it did not include a requirement to innovate with the lifts, now an essential element of station footbridges as part of Network Rail's Access for All Programme to provide accessible routes to and between platforms. They are also the source of most public complaints about existing footbridges.

Network Rail currently relies on 'standard' lifts that are designed for office environments. They require major works on site, including construction of a 'building' to house each lift and excavation of deep lift wells. They also conform to the manufacturers' business model, which relies on follow-up maintenance work. They are also notoriously unreliable and frequently out of service, the most common faults occurring in the door mechanisms.

The consortium brought in SCX Special Projects to look at the lifts. The Sheffield-based company responds to complex and difficult engineering challenges, including mechanical handling for the nuclear industry. Its highest-profile projects are the sliding roofs for Wimbledon's Centre Court and Number One Court, and the retractable football pitch for Tottenham Hotspur's new stadium (The football pitch in three pieces, *Ingenia* 77). The only lift it designed was a specialist fitting for a Royal Navy hospital ship more than 20 years ago.

SCX quickly discovered some of the peculiarities of station lifts. They are often located in areas open to the public and can be subject to rough handling. This can vary from forcing doors open or accidentally dropping a box of screws on the floor (some of which then jam the door mechanism), to behaviour including riding on top of the lift car, camping in the lift well or, in one case, setting fire to a mattress placed in a shopping trolley, pushing the trolley into the lift and pressing 'go', then sharing a video of the resulting inferno on social media. The new lifts needed to be safe and robust.

Unlike the structure of the bridge itself, the lift is a mechanism that will require regular maintenance throughout its life. Maintaining standard lifts frequently requires operatives to stand on the lift roof, and even to sit in the lift well while the lift descends – both with clear (and largely avoidable) safety issues. So the lift design had to simplify maintenance.

SCX established three principles for the new lift: fully modular construction, independent of the adjacent bridge; full commissioning completed in the factory, with the lift then transported to site and simply 'plugged in'; and sufficient redundancy in the mechanisms to minimise downtime.

Most challenging of all were the myriad of British Standards and Network Rail regulations governing the design and operation of lifts, all for very good safety reasons, but presenting a bureaucratic obstacle to innovation and change.

SCX chose to substitute the more conventional hydraulic or cable drive with a belt drive, both to keep the system simple and to provide 100% redundancy. Two motors drive six thermoplastic polyurethane belts, each of which encases 20 steel cords.

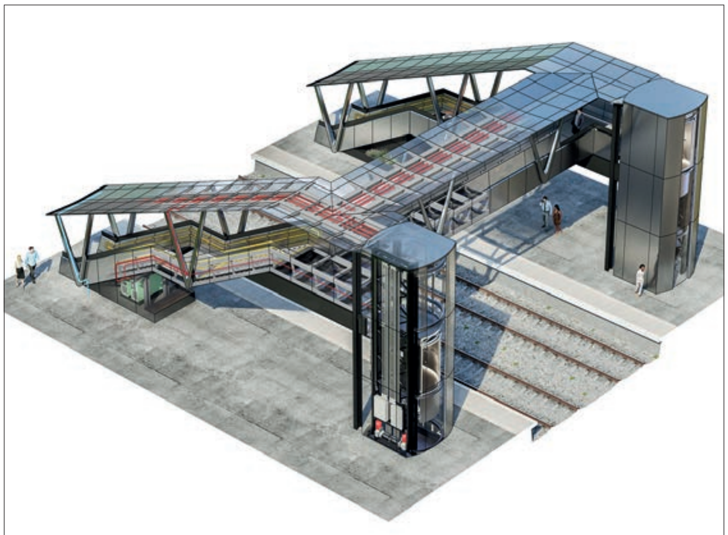
The design's key element was the lift cab itself. This needed to be visually attractive, comfortable to operate (especially for wheelchair users) and reliable – particularly the doors. Current lifts typically have four-part concertina doors with large numbers of moving parts, making them vulnerable to failure. Instead, a semicircular shape was chosen for the cab, with two curved glass sliding doors driven by relatively simple belt mechanisms. To verify its robustness, a prototype of the door is undergoing 24/7 operational tests, including with SCX's 'virtual foot' and 'virtual hand' to mimic blockages, to replicate the 15 million cycle design life.

The two 1.1 metre doors are on opposite sides for simple entry one side and exit the other, but the cab contains a 1.6-metre turning circle, so where site constraints limit the options to a single door, wheelchair users can turn and do not need to reverse out. Passengers also have a continuous view out, through the glass.

The welded tubular steel structure of the lift, clad in stainless steel, is manufactured in three modules: the base and top units, and a spacer module in between. The three units are joined, the mechanisms and cab inserted, and the completed lift is tested and commissioned in the factory. It is then laid flat on a lorry, transported to site, lifted upright and placed alongside the new bridge. It sits on any foundation type and is connected to the bridge by simple expansion joints: the lift is structurally independent and capable of resisting the strongest winds without support from the bridge. The whole installation process is intended to be as quick and simple as installing a new washing machine at home.

Maintenance is assisted by innovative remote monitoring, with alerts sent if repairs are needed. The system's redundancy means the lift can still operate until repairs can be made. Also, all maintainable items are at ground level or within the cab, and access panels and hatches allow full system inspection.

The new lift is already receiving interest for use with other bridges besides AVA.



A cut-away of the bridge and its integrated services, showing the preassembled and precommissioned lifts simply delivered and 'plugged in' like a new washing machine © Expedition Engineering

Critically, mild steel footbridges must be repainted every 30 years or so, causing serious disruption, while stainless steel used for the AVA footbridge should last a lifetime of more than 120 years

two weekends, but the aim is to reduce this to one.

PERFECTING THE PROTOTYPE

As part of the design process, a full-scale prototype was built both to test manufacturing efficiency and to help promote the concept at Network Rail and outside of it. Lessons learned prompted design changes.

As a result, the roof is supported on V-shaped pillars, and although the bridge is open at the sides, a roof increases the winter deck temperature, to minimise the use expensive and corrosive de-icing salts. Inside the bridge and stairways, the finishes are also in stainless steel, folded and bolted. The finishing – including glazing – is done before shipping to site.

The stainless steel sheets are bead blasted (have glass or steel beads shot at them at high pressure) to dull the surface and reduce solar glare, which could distract train drivers. The process creates an attractive finish and does not affect one of the material's main advantages: graffiti can be sprayed with a water jet or wiped off relatively easily. The design also had to discourage other forms of vandalism, including tampering with the structure or climbing on the outside – the engineers employed a solid parapet approach to make it harder to climb.

BENEFITS OF CHANGE

Cost and carbon comparisons with conventional footbridges are complicated by the current high volatility of material and component costs. Stainless steel is more expensive and contains more carbon upfront, but mild steel requires three or four coats of paint after manufacture. Critically, mild steel footbridges must be repainted every 30 years or so, causing serious disruption, while stainless steel used for the AVA footbridge should last a lifetime of more than 120 years and will result in lower whole-life carbon emissions.

Network Rail estimates that current footbridges take 9 to 12 months to construct on site and cost £3 million to £4 million each – less than 17% of which is for the superstructure and materials; the remainder goes towards items such as contractor's preliminaries, project management and risk costs. The AVA footbridge aims to reduce capital costs by a third, time on site by two-thirds and overall project time by three-quarters. There will also be a reduction in whole-life carbon emissions. Its service life will increase by 200% and lift reliability by 100%.

Response to the design has been extremely positive, with the first order – for Stowmarket station in Suffolk – placed even before the 'demonstration' bridge was installed over Network Rail's live test track at Widmerpool in Nottinghamshire later in 2022. However, to achieve the main benefits of factory production, manufacturers of the bridge will need a steady stream of orders. Policymakers make decisions on railway investment separately for each region, and spending on each individual bridge may require Department for Transport (DfT) approval at various stages: for example, Stowmarket bridge has been ordered by local train operator Greater Anglia but required approval from both National Rail and the DfT.

X-Treme Systems believes that at least five orders a year will be required to maintain a production line. There are some 2,500 stations in the UK, some with more than one footbridge and many in urgent need of replacement. If demand grows, the process allows other SMEs (in the UK or elsewhere) with similar robotic equipment to simply take on the manufacture, fed by the same 3D software.

Companies across the world have also shown serious interest, including Irish Rail, Los Angeles Metro, Toronto Metro, Indian Railways, and New South Wales Railways. There is also clear potential for other uses, such as pedestrian bridges over highways, and Network Rail is already looking at how a similar approach could improve station design.

Success with the AVA footbridge could well pave the way for wider adoption of manufactured infrastructure.

Hugh Ferguson talked to Eva MacNamara from Expedition Engineering and to representatives of Network Rail, X-Treme Systems, SCX Special Projects, and Greater Anglia.

Factum Arte's team working on the facsimile of Paul Preaching at Athens, one of the Raphael Cartoons, for the 'The Credit Suisse Exhibition: Raphael' at the National Gallery in London © Oak Taylor-Smith for Factum Foundation

TECHNOLOGY TO RECREATE ARTWORKS

Artworks dating back hundreds of years have been lost, stolen, destroyed, or are too fragile, heavy or integral to their location to be moved anywhere else. Madrid-based Factum Arte is using state-of-the-art technology and manufacturing techniques to 're-materialise' replicas of famous pieces for modern audiences to enjoy or so that they can be housed in the location for which they were intended. Stuart Nathan spoke to founder, Adam Lowe, about the company's work.

Did you know?

- Only a small percentage of the world's art is recorded in high resolution, preventing it from being lost forever if destroyed, stolen or deteriorated
- Modern technologies such as scanning and 3D printing are being used to produce copies of priceless artworks
- Engineers and artists are also using such techniques to restore paintings and even discover if an artwork is genuine

The Cardinal lies on his back; his full regalia billowing in folds on either side of the couch. His eyelids are part-open, revealing eyes rolled back in their deep sockets. His mouth is twisted and hands clasped over his chest. In life, the Cardinal never allowed his portrait to be recorded, so his face is rendered from a death mask. *The Tomb of Cardinal Tavera*, carved by Spanish sculptor Alonso Berruguete, is richly decorated with allegorical figures representing the virtues that the Spanish church believed he embodied, when he died in the city of Valladolid in 1545 as Primate of All Spain and Grand Inquisitor.

However, this particular artwork isn't in Spain. It is in Bishop Auckland, County Durham. It sits in the Spanish Gallery, an art gallery dedicated to Spanish art, history and culture that opened in April 2022, and is a perfect replica of what is believed to be one of the outstanding examples of Spanish Renaissance sculpture. The heavy original is fixed to the floor at the Hospital de Tavera, just outside of Toledo's city walls, founded by Cardinal Juan Pardo de Tavera in the early 15th century.

The facsimile of the Tomb of Cardinal Tavera, made by Factum Foundation for the Spanish Gallery in Bishop Auckland. The original marble work by Alonso Berruguete was recorded in high resolution in the Hospital Tavera in Toledo, in collaboration with Fundación Casa Ducal de Medinaceli
© Oak Taylor-Smith for Factum Foundation

This replica is the work of Factum Arte, a Madrid-based company, founded by British artist Adam Lowe. Lowe prefers to call his team's work 're-materialisations', rather than replicas or copies, and they are only one part of the company's output. Factum Arte uses state-of-the-art techniques to scan and photograph works of art, often revealing details that the human eye cannot see, creating a digital record of the artwork that can be preserved in case of the original deteriorating or even being destroyed. "Only a small fraction of the world's art heritage is recorded, and this poses a huge risk of catastrophic loss to society and scholarship," Lowe says. Variations of these techniques, using archive photography and scans of other works, can even allow artwork that no longer exists to be reverse-engineered and 're-materialised' using techniques including additive manufacturing, CNC machining (cutting into a material), and colour printing.

It's not just museums like the Spanish Gallery that benefit from Factum Arte's work. The organisation has made new versions of artworks such as Paolo Veronese's vast canvas *The Wedding at Cana*: the original, which was removed (some would say stolen) from Venice by Napoleon's troops, hangs opposite the *Mona Lisa* in the Louvre and the re-materialisation is now in the location for which Veronese painted it – the San Giorgio Monastery in Venice – allowing it to be seen in its original context. Factum Arte has also reconstructed Caravaggio's *Nativity*, which was stolen from Sicily in 1969 and is believed to have been destroyed by the Mafia, now restored to the location where the original was cut from its frame; one of Vincent Van Gogh's seven sunflower paintings, destroyed in the US bombing of Japan in the Second World War; and Graham Sutherland's portrait of Sir Winston Churchill, painted for his 80th birthday, which Churchill hated so much that his wife had it burned to ashes.

PRESERVING HERITAGE

Lowe founded Factum Arte in 2001 with Spanish engineer and artist Manuel Franquelo. Initially, it operated as a workshop for contemporary artists to produce some of their work, including Marina Abramović, Anish Kapoor

In 2018, Factum Arte recreated Vincent Van Gogh's *Five Sunflowers in a Vase*, destroyed in 1945, for Mystery of the Lost Paintings, a seven-episode series produced by the Sky Arts Production Hub. By recording the surface of the sunflowers in the National Gallery in London and mapping its brushstrokes over the few surviving photographic references of the destroyed painting, the company's 3D department could recreate the surface of the lost work © Factum Arte

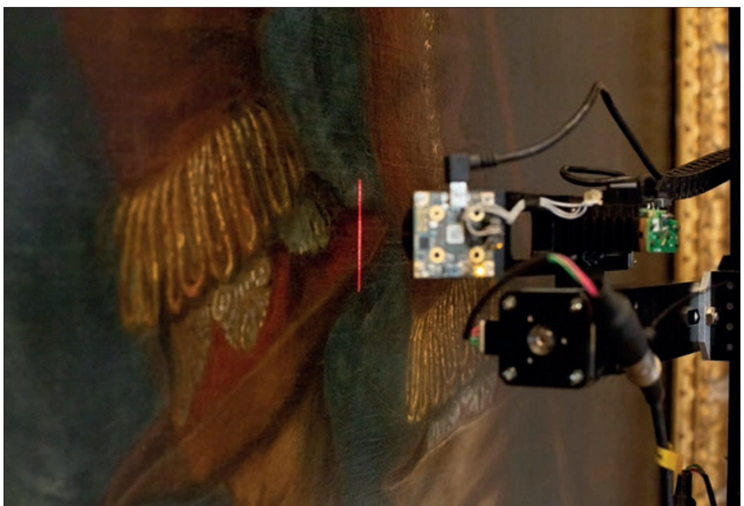
and Mariko Mori. In 2009, Lowe founded the Factum Foundation for Digital Technology in Preservation.

Lowe had been shocked by how little attention had been given to the protection of artistic heritage and was convinced that engineering and technology could help. He says that the use of technology to preserve heritage is underused: "One of the things that shocks me most is when somewhere as important as Notre-Dame burns down: it turns out that the only 3D scan done there was by a US academic casually over a couple of days in his free time. There was no systematic recording of that building using different technologies."

As part of a 2001 project to record and produce facsimiles of ancient Egyptian tombs in the Valley of the Kings, Franquelo, working with a team of artists, conservators and engineers, developed a key piece of technology that is still vital to Factum today: the Lucida scanner. This close-range, non-contact laser scanner records the surface texture of low-relief objects such as paintings and bas-relief sculptures in very high resolution without being affected by the material or colour of the object being scanned. A polished gold surface is recorded with the same fidelity as marble. The foundation had used a variety of commercial 3D scanning systems but had found they were unable to produce accurate data from dark or glossy surfaces. The Lucida scanner moves a thin red laser line across the surface of an artwork, while two cameras positioned at 45° on either side of the line record how it is deformed by the texture it encounters. The integral software processes the captured images as 3D information in real time, while the system stores raw black and white video for future high-resolution post-processing.

The result is a 'depth map'. The camera can move laterally on rails across the surface of an object and can also be pushed closer or pulled further away. Designed as a highly portable system, Lucida is now used at institutions including London's National Gallery and Victoria and Albert Museum, Madrid's Prado, Washington DC's National Museum of Art, and the Louvre. By removing the colour from an object, it allows curators to study details such as an artist's brush strokes, the 'pounce marks' made to transfer designs from a cartoon (a preparatory design on paper) to make a tapestry, or the influence of the texture of a wooden panel on the composition of a renaissance painting.

The National Gallery used the Lucida to scan the surface of Van Gogh's *Sunflowers* to determine the texture the artist created with his use of thick paint so that it could re-materialise the painting of six sunflowers lost in Japan. As the two paintings were produced within days of



Detail of the Lucida 3D scanner recording the surface of *Philip Herbert, 4th Earl of Pembroke, and his Family* by Anton van Dyck at Wilton House, 2020 © Osama Dawod for Factum Foundation each other, Lowe reasoned that Van Gogh would have used the same brushes and possibly even the same paint tubes to make both paintings and that therefore the texture of the brushstrokes on one could be extrapolated to model the other.

Lucida is often used alongside panoramic photography to record an object's colours. Although such devices are used in industry and defence – for thermal imaging in conflict zones, for example – Factum Arte worked with German manufacturer Clauss, which developed the first electronic panoramic camera, to optimise the system. Lighting is a major problem for this application. Factum used a 600-millimetre telephoto lens to capture images, but to achieve optimum focus and depth of field this had to be set to a very small aperture, necessitating long exposure times and making the equipment vulnerable to vibration. To avoid this and speed up the process – time was a factor because the project before the camera was developed involved recording a whole fresco-covered room in the Vatican in three days – the team used an ultraviolet (UV) filtered high-speed flash coupled with a twin lens zoom system mounted on a separate

PRINTING PAINTINGS

Factum Arte uses a variety of techniques to make artworks. Some are drawn from the latest developments in manufacturing technology, while others are not even used in industry yet. They range from casting to advanced milling and include several types of 3D printing. While some of these technologies are used by contemporary artists to make objects, others are more often in use for re-materialising existing or lost art.

Perhaps the most striking example is using 3D printing to make objects that most people might consider to be not three-dimensional at all: paintings. The texture of the surface on which the original artist painted can have an influence on the composition: knots and grain in wood panels could direct the artist on how to place elements of the picture. Some artists' techniques create characteristic 3D texture to their works: both Rembrandt and Van Gogh used very thick paint that they almost sculpted onto their canvases; a technique known as impasto. Almost every artist creates texture with their brushstrokes, which are an integral part of the viewer's experience of looking at a painting.

Factum uses elevated printing to make the textured surface for a re-materialised painting. Similar to flatbed printing, which the company uses in an advanced form to print colour onto surfaces, elevated printing uses an UV-cured polymer ink to build up a textured surface layer upon layer. Each layer is between 10 µm and 15 µm thick and reproduces the depth map recorded using a Lucida scanner (sometimes manipulated digitally) in a physical form.

In general, the print from the elevated printer is not itself used as the substrate for a final re-materialised image but is used to make a silicon mould from which a substrate is cast in a material more suitable for the finished work. Gesso – a binder mixed with powdered chalk or gypsum – is often used, as artists have used it for centuries to prepare the surfaces of materials for painting.

The white textured surface thus created is then printed in colour using a modified flatbed Epson Stylus Pro 1180 printer. The modification allows the operator to overprint very precisely many times using inks of varying opacity. Before printing, Factum's technicians use Photoshop to split the image file into several layers to extract as much information as possible about the different tones present. The deepest layer contains information about the darkest tones and subsequent layers capture lighter tones. Varying the opacity of the ink allows detail that might otherwise be lost in the darkest areas of the picture to be retained. The darkest areas are overprinted the most times to produce a very wide range of dark tones: this can be very effective when printing an image by an artist for whom dark colours are particularly important, such as Joshua Reynolds who often painted his subjects in rich dark clothing.

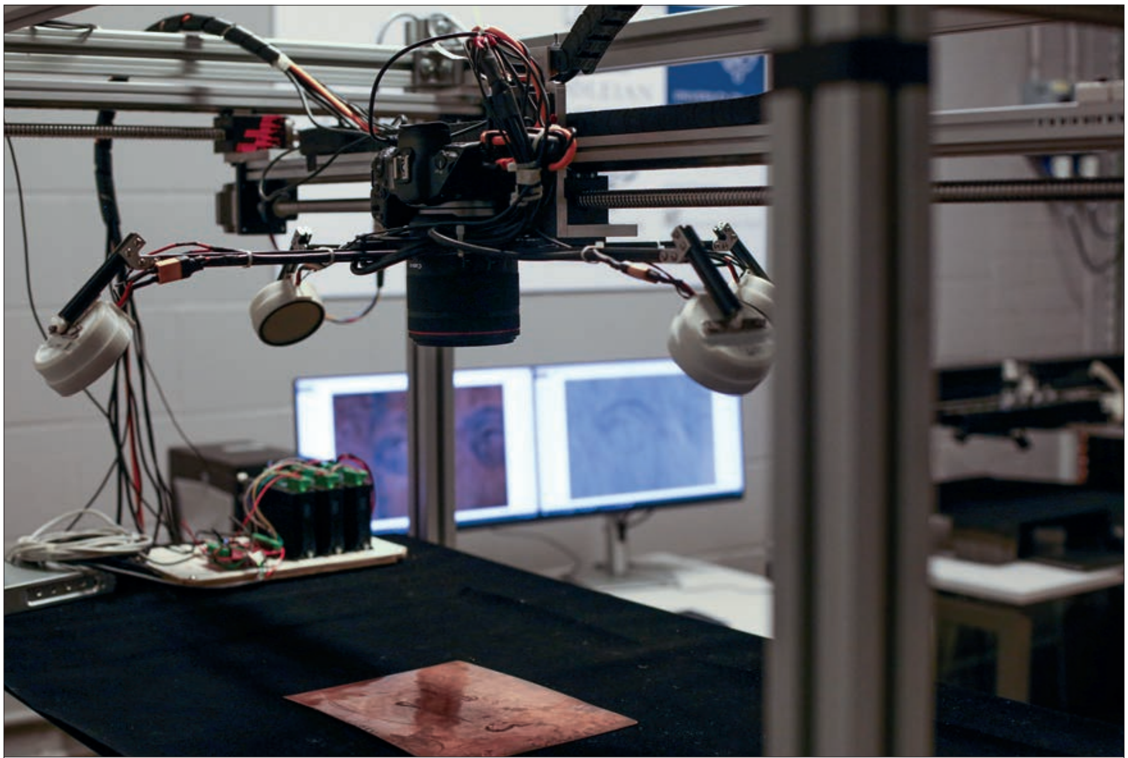
Another benefit of overprinting in this way is that it is very well suited to working on textured surfaces with micron level detail. To ensure that the ink lands on precisely the right position on the surface, a version of the Lucida texture map is first printed onto a clear acetate sheet, which is used to register the printer – that is, to position the printing head to a high precision – before replacing the clear sheet with the textured relief surface.

In some cases, rather than 3D-printing a textured substrate, the surface to be printed is made by routing; this is particularly useful when the relief depth is near or beyond the upper limit of what is achievable using elevated printing. Factum uses industrial routing machines controlled by a combination of commercial and in-house developed software. This technique was used to make replicas of the mediaeval *Mappa Mundi*, owned by Hereford Cathedral: the original map was drawn onto a single sheet of calf-skin vellum, which has, over seven centuries, warped and buckled. Incredibly precious, the original map is displayed behind glass that is only removed every other year. One facsimile was routed from plaster and left unprinted so that blind and partially sighted people can feel it to get an impression of the map's appearance. Another version was colour printed to give a more accessible version of the map in its current state of preservation for study by conservators, researchers and the general public. Routing techniques are also used by some of Factum's contemporary art clients, notably Marina Abramović, who makes objects routed from alabaster.

panoramic head, which allows the flash to be positioned at the optimum angle to minimise reflections.

Factum Foundation is also working with the Bodleian Library on a project called ARCHiOx (Analysing and Recording Cultural Heritage in Oxford), which uses another new piece of equipment alongside Lucida – a prototype photometric stereo photographic system called Selene. Developed for capturing surface texture and colour of flat or nearly flat objects such as paintings, murals and sculptural bas-reliefs simultaneously, Selene captures 2D images under several different lighting angles and combines them electronically. Four flashes are synchronised using an electronic board to work with a mirrorless camera on a motorised mounting to scan documents, printing plates and other objects. "It's the first time that any major library anywhere in the world has focused on 3D recordings of their objects," Lowe says. "People talk about the material culture of the book with great reverence. But when it comes to digitising libraries, it's very much a case of extracting information from the books so you can have it in a digital format. We wanted to show that if you also have 3D recording, you can start to see and understand the object in very different ways."

The ARCHiOx project has recorded several 18th and 19th century etching plates from the Rawlinson, Lister and Gough collections, including a design identified as the work of William Blake, to an accuracy of 25 µm. "Being able to record an engraving with enough resolution to make a 3D print of it on an elevated printer, and then to make a print from that replica, is incredibly exciting," Lowe said. The system was also used to scan Sanskrit manuscripts scratched into the waxy surface of palm leaves centuries ago, with equally striking results. He adds: "As the leaf ages and browns, it becomes unreadable. But with Selene, we could record the surface and extract the Sanskrit script very, very clearly. This to me was a real excitement."



The Selene Scanner installed and operating at the imaging services department of the Bodleian Library, recording a copperplate from the Lister Collection © Bodleian Libraries

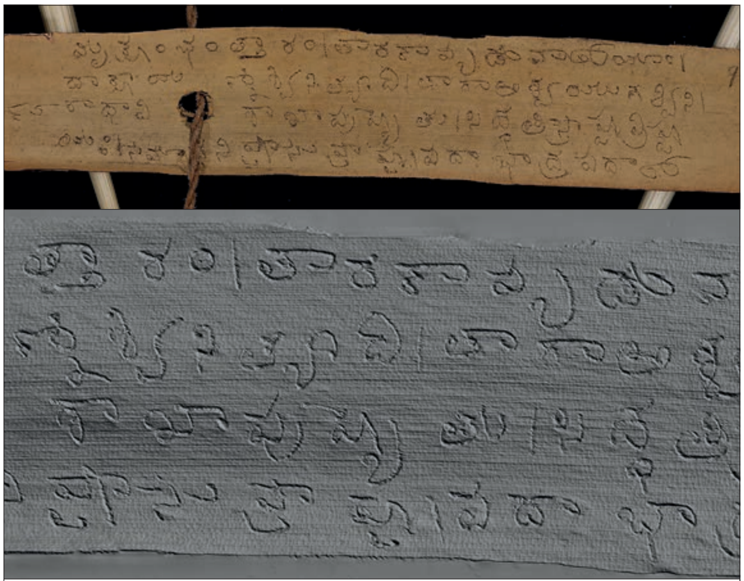
Another part of the project involved scanning an eighth century manuscript. "In the margin of the borders, we recorded letters that have never been seen – inscriptions and writing that can't be seen by the human eye. It's the first time, I'd say, we've actually got a clear result where no one was expecting it at all."

Making physical objects for Factum Arte involves both additive and subtractive techniques. "We use primarily now, what we call elevated printing, which is a 3D-printed technology based on multiple layers of UV-cured ink," says Lowe. "It uses electrostatics to attract the ink particles and the UV light hardens it in layers. Each layer is about 10 µm thick, so 100 layers get you to a millimetre. We use that to build the relief texture, but not the colour because the UV ink has a volume: it doesn't look like oil paint. We've built piezoelectric printers in-house for printing colour. So we'll build the volume of the brush marks with elevated printing, but we need a different character of ink to get the colour on top."

Subtractive techniques include three- and seven-axis CNC milling, often to make moulds into which re-materialisations are cast. For the *Tomb of Cardinal Tavera*, moulds were made from physical stereo-lithographic prints and the monument itself cast in sections out of a marble composite. These sections were then joined together and hand-painted to replicate the patina (an aged finish that forms naturally over time) of the original.

ARTWORKS UNDERSTOOD

As well as producing re-materialisations, Factum's techniques can be used in restoration. For example, Lowe worked on a portrait by Sir Joshua Reynolds whose varnish had yellowed badly over time, a common problem with old paintings. Usually, restorers remove yellowed varnish with a solvent to reveal the original pigments beneath. But Reynolds, a relentless experimenter, habitually tinkered with the composition of his paints to achieve illusionistic effects. The result of this was that dissolving



Detail of the *Palm Leaf Manuscripts,* from the collection of the Bodleian Libraries, recorded in colour and 3D using the Selene Scanner. The shaded render of the 3D data clearly shows the Sanskrit characters etched in the surface © ARCHiOx

the varnish would also have dissolved the pigmented glazes that Reynolds used to make the painting. Comparing the portrait with less deteriorated Reynolds works to determine precisely which pigments he had used, Lowe's team digitally removed the yellow cast from their colour scan of the painting and printed this image onto a 3D print of the wooden panel on which Reynolds had worked. "Conventional restoration would have lost everything that made the painting specific, so they decided they couldn't touch it. We were able to do more or less what a restorer would do, but without ever physically making contact with the paint surface."

Lowe believes that Factum Foundation's techniques can even enhance understanding of artworks. "There's a whole new world of data analysis. Whether it's based on machine learning or artificial intelligence, both are dependent on pattern recognition and number-crunching on a very large scale. I'm pretty certain that from the surface data we are recording, we will in time be able to attribute the hand of specific artists with great degrees of confidence. I'd be very surprised if we can't record paintings by El Greco and say, 'El Greco painted this part himself, his son Jorge Manuel painted this part, and several studio assistants painted these bits over here'." Lowe is currently working on a project to test this theory with a team from the physics, materials science and engineering, and art history departments at Case Western Reserve University in Cleveland, Ohio [see box].

Though not himself an engineer, Lowe's experience with mechanical, electronic, and software engineers has left him with a deep appreciation for the way that the disciplines mesh and collaborate, especially on projects that might seem to a layperson to be well out of their comfort zone. "I would love everyone to get excited by the way that engineering is now playing very creative roles in the production and preservation of works of art. For me, this is a beautiful example of what happens when people work together."

A QUESTION OF ATTRIBUTION

One of the most ambitious projects at Factum Foundation is its collaboration with Case Western Reserve University (CWRU) in Cleveland, Ohio, to develop ways to use Factum's digital recording techniques to determine a painting's attribution. The study aims to teach artificial intelligence systems to recognise the distinctive way that artists form brushstrokes on canvas, similar to handwriting recognition. This could not only give a valuable new way for the art world to determine whether a picture is genuine or a copy, but could even determine which members of an artist's workshop contributed to a finished work and which parts were painted by whom.

Initially, the goal of the project is to study late works by El Greco, the Crete-born artist best known for his work in 16th-century Spain. He established a workshop in Toledo where he took on students, including his son Jorge Manuel, who worked with him as assistants. El Greco often painted only the portions of his large artworks that he considered most important himself and entrusted his students to reproduce his high idiosyncratic style in the other parts of the pictures; a common practice for artists of that and other periods. It is partly for this reason that El Greco's work is often the subject of debates about attribution.

A team from CWRU's department of physics, materials science and engineering developed the system. Using several paintings of lilies by students from Cleveland Institute of Art, four artists created three virtual 'patches' to areas of the paintings to simulate how assistants might have worked on them. The analysis focused on the subtle detail that can be thought of as the dynamic movements of the bristles as they respond to each hand. In reality, the analysis is numerical and is looking at the paintings in different ways. After training the system on the 'patches' produced by each artist, the system successfully identified 98% of them, connecting them to other samples made by the same hand.

BIOGRAPHY

Adam Lowe is the Director of Factum Arte and Founder of Factum Foundation for Digital Technology in Preservation. He was trained in Fine Art at the Ruskin School of Drawing in Oxford and the Royal College of Art in London. He has been an adjunct professor of the MS in Historic Preservation at Columbia University, New York, since 2016. In 2019, Lowe became a Royal Designer for Industry, awarded by the Royal Society of Arts. He has written extensively about originality, authenticity, and preservation.

FROM TREE TO TOILET: ENGINEERING LOO ROLL

© Shutterstock

It takes complex technology to turn trees into toilet rolls. Wood processing, chemical engineering and mechanical engineering all play a part in delivering rolls with the right size, texture and properties. Pandemic panic brought home how we depend on this vital product. Dr Anna Ploszajski unravels the engineering behind and production of one of life's essentials.

Did you know?

- The UK uses about 1.3 million tonnes of tissue a year, according to the Confederation of Paper Industries
- Some estimates put the number of toilet rolls that an average British consumer uses per year at 127 rolls – but only 30% of the world's population uses toilet roll
- Engineering is involved throughout the whole toilet roll production process and engineers are coming up with ways to make it more sustainable and efficient

Engineers get up to many things. You'll sometimes find them stroking a concrete wall or leaning precariously off the side of a bridge. You might catch one smiling at an aeroplane the way others would at passing dogs or children. Nothing escapes an engineer's attention. Then there are engineers who, even as you read this, are sitting on the toilet, trapped there by a humble toilet roll. From terrifying machinery to subtle chemistry, engineering touches toilet paper at every stage of its life, from tree to toilet.

Toilet paper is almost entirely cellulose – the main substance that makes up the cell walls of plants. This means that toilet paper decomposes quickly in sewage systems but is not too fragile so as to lose structural integrity at the most crucial moment of use.

FROM FORESTS

Toilet paper's raw materials are fresh or recycled wood, or recycled paper products. In the former case, the wood usually comes from pine trees – a large tree can produce up to 1,500 toilet rolls. The process for felling the trees varies by region, from hand-wielded chainsaws to highly technical automated machinery, but the steps are the same: the trees are felled, branches removed, and logs cut to standard lengths ready to be turned into wood chips.

Perhaps the most impressive methods of collecting wood from trees are in Sweden and Finland, where lumberjacks use machines called tree harvesters. The machine's head grips the base of a tree and a chainsaw cuts across the trunk. The tree harvester's chainsaws are hydraulically powered, making them much more powerful than handheld devices.

Still gripping the base of the trunk, the head rotates as the tree falls to the ground. Once horizontal, two feed rollers grip the trunk and pull it through the head at great speed. It passes through two or more 'delimbing knives', which strip all the branches off the trunk in seconds. Mechanical sensors measure the trunk's diameter and adjust the delimbing knives accordingly. A wheel measures the length of trunk, and the chainsaw cuts the stripped trunk into logs with predetermined length, ready to go to the woodchipper. Computer algorithms tweak the whole process and adjust the different parameters to maximise how many branch-free logs each trunk produces.

Next, a debarking machine removes the bark. A log is mounted horizontally on a series of rough wheels that grip and slowly spin it under a moving cutting head. The head optically scans the shape of the log and controls the blades to shave off just the right depth of bark to conserve as much of the precious inner wood as possible.

A tree harvester in action © Wikimedia Commons

The bare logs are now ready for a chipper to transform them into workable wood chips. These machines are similarly large-scale, often as large as a tractor, and as intimidating as the harvester and debarker. A hopper guides logs into the jaws of the chipper, which can be either a rotating disc with blades on – a bit like a rotating cheese-grater – or a rotating drum with blades on its outer surface. Either way, the chipper ejects the shredded log chips from a chute for storage. Grooved rollers grip and push the logs through the chipper, keeping workers at a safe distance. These powerful chippers, typically hundreds of kilowatts, are usually powered by an internal combustion engine.

Wood is a composite material made from fibrous cellulose (a linear polymer) and hemicellulose (a cross-linked polymer) held together in a matrix of glue-like lignin, a bit like a natural carbon-fibre reinforced plastic composite. Once chipped, the wood is ready to give up its precious cellulose in the pulping process, also known as the kraft process ('kraft' meaning 'strength' in German). Here, wood chips are heated to about 170°C in digesters under pressure with water, sodium hydroxide, and sodium sulfide. This breaks the chemical bonds between the cellulose, hemicellulose, and lignin components, so the cellulose can then be recovered.

The cellulose fibres are usually 1 to 2 millimetres long, and about 30 micrometres wide – the width of a fine human hair. The straighter and longer the fibres, the stronger the resulting paper. Mechanical action at the pulping stage can shorten the fibres, and introduce kinks and curls, all of which results in weaker paper. However, tissue paper is designed to be easily ripped so damaged fibres aren't necessarily too much of a problem.

The whole process is made as efficient as possible; the slurry of cellulose fibre pulp that comes out of the kraft process is heated to separate the pulp from the pulping chemicals, which are recovered for reuse. High pressure steam generated by the recovery boiler can feed turbogenerators to provide electricity for the mill or nearby industries, or feed onto the grid for local communities.

Once the cellulose is recovered, it is diluted with water to create a suspension of 0.5% fibre. This is then screened, washed in stages and bleached to make it white.

RECYCLED ROLLS

Some toilet paper is made from recycled paper. The recycling process produces damaged fibres, but this is usually an acceptable feedstock for toilet tissue. Recycled paper is often mixed with new pulp to maintain enough mechanical integrity in the end product.

The recycling process mixes wastepaper with water and agitates it in a pulper, a machine not dissimilar to a washing machine. This allows metal or plastic contaminants to sink to the bottom and be removed. That is not the end of the clean-up process for recycled paper. Some inks contain toxic heavy metals such as lead, cadmium, and hexavalent chromium, which must be removed and disposed of safely. (To ensure the safety of recycling processes, these inks are being phased out of the production of recyclable materials.) In the next step, air bubbles are blown through the gloopy pulp. Ink particles attach to air bubbles and form an inky foam that is skimmed off, leaving the rest of the pulp ink-free. Next, the pulp is squeezed through rollers to remove some water and passed through a contraption of revolving knives to break it up.

After this point, the process is the same, regardless of raw material, new or recycled pulp. The watery pulp suspension is sprayed onto a continuously

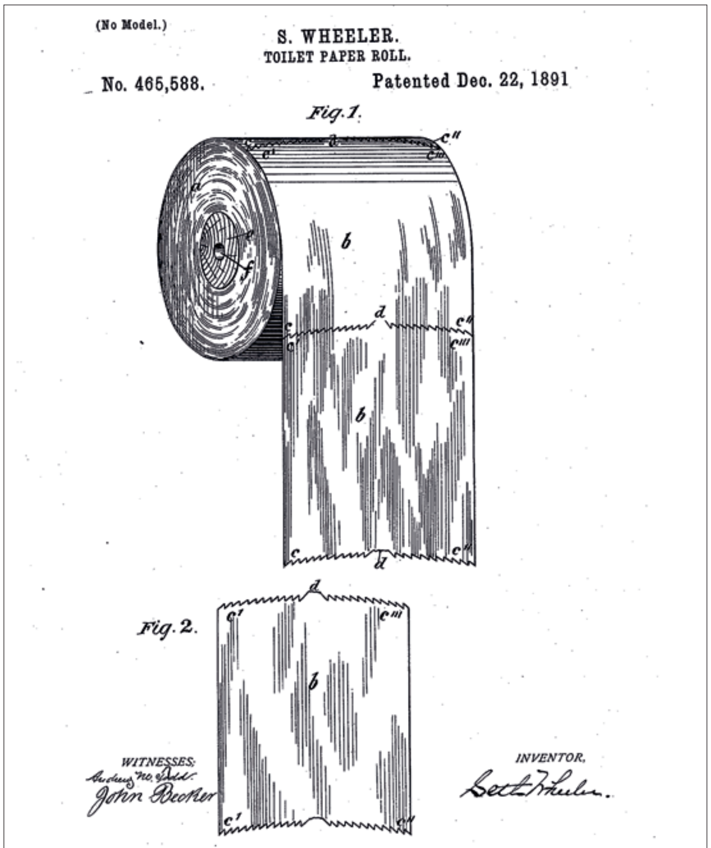
PAPER IN THE BEGINNING

A brief history of toilet paper can tell us a lot about society, education, and industry. Paper itself was invented in China in about 100BC. For over a millennium, papermaking remained a batch-production process. Sieve-like moulds were lifted through watery suspensions of wood pulp. The captured fibres formed a matted layer that was compressed and dried to form paper sheets.

The Ancient Chinese did use paper as toilet paper, but it didn't catch on further afield, partly because this labour-intensive process made paper a valuable commodity. It wasn't until the dawn of the printing press in 15th century Europe that paper was adopted as a writing material elsewhere, because it out-performed its material rivals, papyrus and parchment, when used in the printing press.

The printing press brought about a high demand for mass-produced paper, and eventually led to the continuous roll-to-roll processes for large-scale papermaking in the early 19th century. This produced cheap, mass-produced reading materials and newspapers, widening access to education for women and the lower classes. It was in these forms – everyday scrap paper such as bags, letters, envelopes, and newspapers – that paper first found use in European bathrooms.

The first paper sold just for bathroom use in the western world in the late 19th century was produced by the British Perforated Paper Company and the Scott Paper Company in the US. These early iterations came in single pieces, sold in discrete cardboard boxes. The roll-based version that we know and love today followed in 1891. In case you were wondering, in his patent, Seth Wheeler of Albany, New York, showed the available end of the roll in an 'over' configuration.



The toilet roll diagram from Seth Wheeler's patent application

moving screen of a very fine stainless-steel mesh. The process forms a wet sheet of matted fibre over 1.5 metres wide. The fibre sheet runs through hot rollers at over 150°C, which dries it in less than a second. This produces a continuous roll of delicate paper that is just 0.1 millimetre thick. The result is a spool of paper around 75 kilometres long.

A creping process follows to create the required texture and structure for tissue paper. Creping involves a sharp blade scraping the paper off the dryer to create a slightly crinkled sheet. This helps to improve the paper's flexibility and absorbency. Creping also weakens the paper so that it will disintegrate when wet. Next time you're in the loo, notice the subtle stretch in your toilet paper – that's thanks to the creping process. Next, perforating machines stamp rows of holes to perforate the paper into rippable sections. At this stage patterned rollers can also emboss a pattern onto the paper, which also helps with absorption.

ON A ROLL

Elsewhere in the factory, recycled cardboard inners are made by winding two strips of thin recycled cardboard around a core to make a tube, which the new paper is then wound onto. Two sheets are simultaneously fed onto the tube, one from above and one from below. The sheets come together as they are wrapped onto the cardboard inner to form two-ply toilet paper.

Once the roll has been wrapped to the right size, a long blade cuts the paper and a machine automatically seals the end with glue to stop it unravelling. At this stage, the toilet paper is still on an extremely wide roll. The final stage is for a circular saw to cut the wide roll into standard-width rolls that are then automatically packaged in paper or plastic. In this way, toilet-paper factories can produce millions of rolls every single day.

Like many engineering topics, the production of toilet rolls still has its challenges. For example, materials engineers are studying toilet paper in finer and finer detail to better understand its structure–property relationships, hoping to close the loop further on recycled paper products. Manufacturing engineers seek to make marginal gains in the manufacturing process to make it more resource and energy efficient.

One organisation making a change is Australian startup company Who Gives a Crap. Its plastic-free products are made entirely from recycled feedstocks and the founders donate 50% of the enterprise's profits to partners including WaterAid, Splash, and Sanergy, who build toilets and improve sanitation in lower-income countries. Their donations have amounted to almost 11 million Australian dollars at the time of writing. About two billion people in the world don't have access to a toilet and contaminated water contributes to over a million deaths a year, when human waste ends up in local waterways – by being sold in this way, the humble toilet roll is indirectly helping to improve sanitation and save lives globally.

And seismic shifts in consumer priorities, from increased costs of living to higher demands for sustainability, may further shake up the industry as a whole; will there be new products designed to do away with toilet paper all together? These are the thoughts swirling round the heads of the engineers stuck on the loo as you read this, from tree to toilet, and beyond.

PANIC BUYING

Toilet paper made headlines in March 2020. More specifically, it was its absence that was particularly notable and distressing. Despite retailers reassuring us that there were no shortages, consumers began hoarding and pushed supply chains to breaking point. This left many of us facing empty shelves and empty toilet roll holders at home.

This sudden spike in demand exposed the weakness in the UK supermarkets' 'just-in-time' supply chain model. Here, every link in the chain supplies to the next link only when it is needed. In normal times, the just-in-time model reduces waste, lowers costs, and increases the efficiency of the supply chain. But March 2020, as the COVID-19 pandemic gripped the world, was anything but 'normal'.

It's tempting to think of a supply chain as a linear sequence of businesses, from raw materials to supplier, manufacturer, distributor, retailer, and consumer. In reality, most modern supply chains are complex networks of actors based all around the world. Manufacturing engineers use complex models to fine tune supply chains, trying to get the right balance between efficiency and resilience against unexpected circumstances.

Few could have predicted that a global pandemic would lead to a short-term shortage of toilet roll in my local Tesco, but there are other global shifts that are easier to foresee. One of these is a shift towards sustainability at all points in the supply chain, from tree to toilet.

Toilet paper is, of course, designed to be single use. Estimates vary, but toilet paper may account for 10% to 15% of deforestation worldwide, with about 27,000 trees-worth of toilet paper flushed down the world's loos every day. Although wood is generally seen as a renewable resource, other faster-growing sources of cellulose could help combat deforestation, such as fast-growing bamboo and bagasse, a by-product of the sugar industry. And, compared to other products, the single-use nature of toilet paper means that any loss of performance that results from using recycled paper feedstocks can mostly be compensated for in green credentials gained.

Other areas for improved sustainability in the manufacture of toilet paper include reducing water usage, bleaching with chlorine-free chemicals, and reducing the diameter of the cardboard inner tube to improve shipping efficiencies.

BIOGRAPHY

Dr Anna Ploszajski is an award-winning materials scientist, writer, presenter, podcaster, performer, trainer, and storyteller. She is a materials generalist, equally fascinated by merino wool as stainless steel, through all the wonderful metals, plastics, ceramics, glasses, and natural substances that make up our material world.

REIMAGINING THE ZOETROPE

Charon **at Burning Man festival in 2011** © Mitzi Peirone

An installation from this year's Greenwich+Docklands International Festival is a life-sized, vertical zoetrope that uses time-honoured engineering principles to display a stunning three-dimensional short animation. Neil Cumins investigates the science behind this super-sized kinetic sculpture, *Charon*, by artist Peter Hudson and crew.

During the first 10 days of September 2022, the skyline of Canning Town's Limmo Peninsula looked a little different to usual. Each night, a vertical zoetrope almost 10 metres in height, lit by strobes and powered by human volunteers, showed a 3D animation depicting the ferryman from Greek mythology, Charon. This art installation arrived from Nantes, on its tour of art festivals around Europe, and was originally devised for Nevada's Burning Man festival in 2011.

Zoetropes are one of the earliest form of animations, dating back to the 1800s. Historically, they consist of a cylinder with a progression of images inside and slots to peer through. As the wheel spins, the rapidly changing sequence of images gives the viewer the illusion of movement, with the slots preventing the images from blurring into one. While at first based on strips of paper with sequences of illustrations (not unlike a flipbook), later developments would go on to use photographs and even sculptures. Most zoetropes are toy-sized, intended for entertainment long before the world of film arrived; but in recent years, a handful of artists have built larger scale installations designed to wow audiences. However, it is by no means a common artistic medium. Mat Collishaw, one of the Young British Artist group, has exhibited several 3D zoetropes, some up to three metres across (coincidentally, his 2014 zoetrope *All Things Fall* was produced in collaboration with Factum Arte – see 'Technology to recreate artworks', page 20, to read about some of the company's other work). But the zoetropes designed by San Francisco visual artist Peter Hudson are some of the world's largest, measuring up to almost 10 metres in diameter, and have been displayed at well-known festivals from Burning Man to the UK's Secret Garden Party.

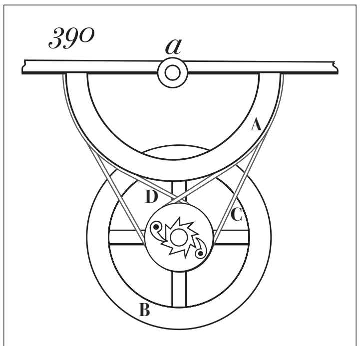
MECHANICAL INSPIRATIONS

The Victorians had an impressive influence on everything from engineering to entertainment – and sometimes both at once. In 1868, Henry T Brown published a book called *Five Hundred and Seven Mechanical Movements*, including detailed illustrations of kinematic concepts important for engineers, from rotating pulleys to pendulums. A 1908 edition included detailed

A modern replica of a Victoria zoetrope © Andrew Dunn

illustrations of concepts such as epicyclic gear trains – also called planetary gears, today used in everything from cars to 3D printers and pencil sharpeners – and capstans, the rotating machines used by sailors to haul weights (such as anchors). It also included a diagram demonstrating how to convert an oscillating semicircular frame into rotary motion.

Fast-forward to the start of the 21st century, and this diagram became a source of inspiration for Peter Hudson. He had spent the noughties creating a series of stroboscopic sculptural zoetropes, depicting everything from recurring universes to people swimming. However, Hudson's previous projects had all been horizontal zoetropes, and he had something more ambitious in



Representation of a device that can convert oscillating motion into rotary motion. A semicircular piece (A) attached to a lever working on a fulcrum (a) is attached to the ends of two bands (C and D). The bands run around two pulleys, loose on the shaft of the flywheel (B). One of the bands (C) is open, and the other (D) is crossed. Pawls attached to the pulleys engage with ratchet-wheels on the flywheel shaft when piece A turns in either direction, producing continuous rotary motion. Image reproduced from 507movements.com, where many scans and animations of concepts from *Five Hundred and Seven Mechanical Movements*, can be found

mind for his next design, which he was due to create for the 2011 edition of Burning Man festival.

RITES OF PASSAGE

Hudson's idea for the new project was to create an interactive depiction of Charon, the Greek mythological ferryman, who carried away departed souls across the river

The central structure of *Charon* visible from below. Participants can be seen pulling on the ropes to generate torque in the far right of the image © Trey Radcliff Haron

Styx to the afterlife. This was to tie in with the theme of that year's festival, rites of passage, and Hudson chose to focus on the final rite of passage: death. The work was to be funded by a grant from the festival and multiple fundraising campaigns, with over 100 volunteers pitching in to construct the zoetrope. The zoetrope would be powered by audience members pulling ropes to create torque (rotational force). After exceeding a certain speed, the 3D animation would become apparent. The choice of ropes was a nod to cathedral belfries, where ropes are used to ring a bell.

A vertical zoetrope of this scale had never been attempted before, and logistical challenges immediately arose from this Ferris wheel-esque design. Most important was the need to translate linear force from people pulling ropes to torque that could drive the rotational motion of the vertical zoetrope. The solution lay in Brown's Victorian handbook, and the aforementioned diagram. It depicted a semicircular piece attached to a lever resting on a fulcrum, with two pulleys connecting it to a flywheel. A continuous rotary motion is maintained as the semicircular piece turns first one way and then the other. For aesthetic reasons, Hudson employed the same principle, but used 12 30-centimetre-diameter drums with custom clutch bearings. With this setup, the force produced by volunteers pulling ropes would be translated into torque to drive rotation of the zoetrope. This spinning motion, when allied to strobe lighting, creates an effect akin to a three-dimensional motion picture, and requires a rotational speed of 20 rpm (revolutions per minute).

OVERCOMING CHALLENGES

Hudson's first horizontal zoetrope had a central rotational axis sandwiched by two tapered roller bearings, requiring only one support point. By contrast, some of his later horizontal zoetropes were supported by idler wheels, but each extra load point increased drag. Instead, *Charon*'s entire rotating structure would rest on a single hub (with four bearings). This vertical zoetrope would require both left and right support points and two tapered roller bearings on each side – all correctly aligned in space.

Furthermore, early prototypes relied on components from bicycle sprockets, which repeatedly failed because of the sheer torque being generated by *Charon*'s human participants. Eventually, an equivalent component from a Raptor quad bike was sourced, which could handle over 1,000 Newton-metres of torque. Another early setback involved the use of manila hemp rope. Not only did this struggle to grip each eight-inch custom-machined aluminium drum satisfactorily, but it also rubbed against itself creating friction and drag that contributed to premature wear. The solution involved encasing each rope in a repurposed fire hose, which had the twin benefits of increasing grip and minimising abrasion. Similarly, sharp internal hex-nut edges on the directional guide pulleys were discovered to be shredding the ropes. These hex-nut edges were sanded down, with Teflon rope glides employed to reduce wear.

The model skeletons spaced around the zoetrope, each adopting a unique pose to give a sense of the rowing motion © Mitzi Peirone

Next, attention turned to the skeletons that would comprise *Charon*'s zoetropic effects. Each model was made from polyester resin and urethane foam, with the skulls, femurs and ulnas custom-cast from foam and polyester resin. The more fragile torso components were purchased from a medical-grade vendor since there was no need for these to move. The team invented a malleable and posable armature that the bones could be situated around, in what would become their final position, with a pivot point at the hips. Next, modelling software was used to create an animation that involved each skeleton adopting a unique pose, to contribute to the sense of movement as the wheel rotated.

MOTION PICTURE

In motion, the results of this modelling software and skeletal positioning are spectacular. Accompanied by the sound of a tolling bell, flame-coloured lights flicker around two Gothic A-frame archways with the wheel centrally mounted between them. A dozen participants tug on ropes that additionally serve to ring the bell. Once the six pairs of ropes are being pulled at a suitable speed, a strobe is activated that reveals the animation of the skeletons inside the wheel as they 'paddle' towards the unknown using wooden oars, creating an otherworldly effect as it towers above spectators. The frame itself – like much of *Charon* – is manufactured from I-Beam steel, contributing to a gross shipping weight of over 8,000 kilograms. Once fully erected, the zoetrope reaches nearly 10 metres tall.

The spinning wheel has a diameter of almost nine metres, with 20 spokes each supporting an animated skeleton, in various rowing positions. The wheel rests inside two double-strut A-frame support arches with cross bracing at both ends.

BUILDING TENSION

Assembling *Charon* takes up to five days, partly because each side of the wheel has to be in perfect alignment. Two parallel points must be exactly square and level, within one millimetre of each other, to align the hub bearings. The team achieves these tolerances by using a five-beam laser. The assembly and transportation process has been further optimised by numbering every item, allocating it a dedicated place within its transportation containers, and ensuring each item is unloaded in the order of assembly. For instance, skeletons are attached to the wheel at 180-degree, then 90-degree, then 180-degree positions, maintaining wheel balance and preventing its weight becoming unequal. A variety of custom dollies, high-density polyethylene glides and platforms are used for moving components along with a forklift truck, a 10-metre tall variable reach lift, a cherry picker, and a crane.

The entire structure is accommodated in two 24 metre shipping containers, and the installation manual alone extends to over 50 pages, with a team of 10 people employed to assemble *Charon*. Disassembly is quicker, taking three to four days, at the end of which a crew of six people is allocated portions of a grid pattern to check *Charon*'s former location for misplaced hardware. When in the desert they even use magnets to identify and rescue any components that have become submerged in the ground. Nothing can be left behind from such a meticulously engineered assembly, especially one that is constantly touring around the world.

THE PRINCESS ROYAL SILVER MEDALS

The Royal Academy of Engineering established the Silver Medal in 1994 to recognise an outstanding personal contribution to British engineering that has resulted in successful market exploitation. In 2021, the Academy's Royal Fellow, HRH The Princess Royal, allowed the Academy to rename its Silver Medal, to honour Her Royal Highness's outstanding contributions as a Royal Fellow and as an exceptional champion for engineering, including as a vocal and longstanding supporter of women in engineering and science.

HEBA BEVAN OBE
CEO AND FOUNDER OF UTTERBERRY

Heba Bevan OBE is the CEO and Founder of UtterBerry Ltd, a patented, wireless sensor system that consists of a collection of miniature, artificially intelligent, ultra-low-power sensors. The technology has been used in a variety of major national infrastructure projects including London's Crossrail and Thames Tideway, with customers including Network Rail, London Underground, Thames Water, Laing O'Rourke, Costain, BAM, and BFK.

Heba is a businessperson and engineer with a track record of technical innovation in the areas of wireless sensor and sensor network design. She is passionate about technology design and expanding STEM education and hi-tech manufacturing in the UK. Her technical expertise includes artificial intelligence, machine learning, robotics, blockchain, optics, semiconductors, and communication systems.

After graduation Heba worked for the microchip design company ARM. She returned to academia to study low-power wireless sensor networks at the University of Cambridge, and it was during her PhD in 2013 that she founded UtterBerry.

Heba was awarded an OBE for her contributions to technology, innovation and STEM education 2018. In 2021, she received the Woman of the Year Innovation Award. Heba is committed to sustainability and the application of engineering to create new sustainable technologies in the electronics industry. She participated in COP26 and supports the government in international engagements related to sustainability.

PROFESSOR DANIEL BRETT AND PROFESSOR PAUL SHEARING

UCL ELECTROCHEMICAL INNOVATION LAB

Professor Daniel Brett and Professor Paul Shearing launched the Electrochemical Innovation Lab (EIL) at University College London in 2011. The EIL is now a leading centre for technological innovation in electrochemical technology in the UK, with more than 100 researchers providing solutions that are critical to achieving net zero. It has supported the formation of several companies in the sector, including that work in low-cost fuel cell engineering, fast-charging technologies for advanced batteries and low-cost hydrogen electrolysers.

For more than a decade, the EIL has successfully operated at the intersection of university and industrial research, securing more than £45 million in collaborative R&D funding. The EIL also provides researchers with mentoring and training in commercialisation to support the market exploitation of new solutions.

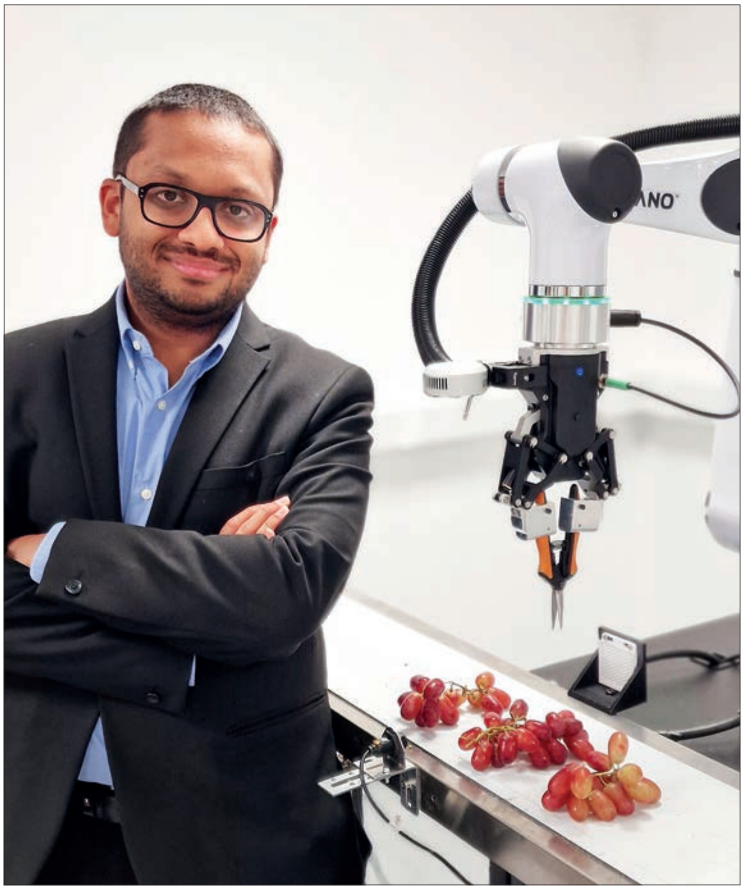
Professor Brett and Professor Shearing are co-founders of The Faraday Institution, the UK's independent institute for electrochemical energy storage research. They are members of its Expert Panel, and lead and participate in several major research programmes. As Founders of the STFC Batteries Network, they have acted as ambassadors for UK science on an international stage, and frequently advise the UK government on policy matters. As leading academics, their combined achievements have enabled widespread scientific, commercial and policy impact, exemplifying the spirit of collaboration that is a cornerstone of engineering practice.

DR ATIF SYED

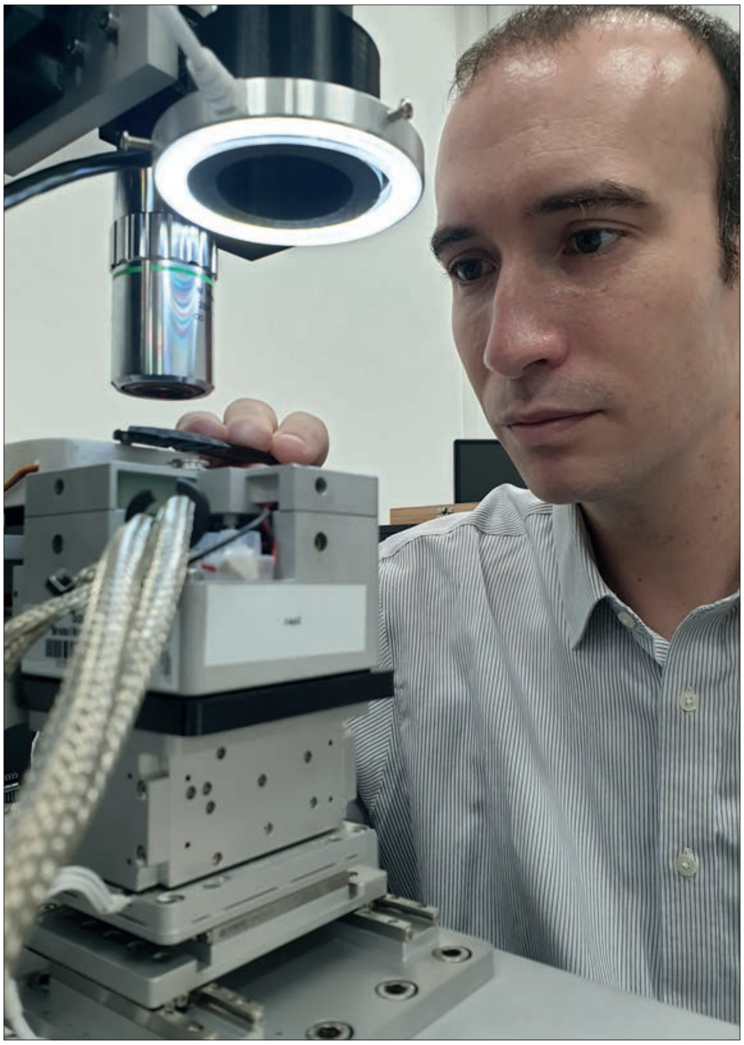
CEO AND FOUNDER OF WOOTZANO

Dr Atif Syed has a PhD in engineering and electronics focusing on developing next-generation flexible and compliant sensors. The Academy awarded him with an Enterprise Fellowship in 2018. His work resulted in the development of a new electronic skin – further developed in County Durham-headquartered Wootzano Ltd, which he founded in 2018. The electronic skin is being used in Wootzano's robotic fruit and vegetable packaging system, Avarai. Fruit and vegetable packers across the world struggle to hire human workers and maintain quality consistently in an industry with razor-thin margins. Avarai uses a patented electronic skin, coupled with machine learning, electronics and custom end-effectors, which enables the system to estimate weight, cut fruits to weight and sizes, identify defects and measure quality, and pick and delicately place into punnets based on end retailer specifications. The electronic skin can be stretched at least 150% without damaging the metallic contacts on top of it. It is food-safe and uses robotic end-effectors to delicately pick and place soft fresh produce – previously a difficult task for robots to complete without bruising or damaging the food.

Wootzano now holds 25 patents covering all aspects of the Avarai robotic system. Dr Syed's extensive expertise in electronics, nanotechnology, robotics, and artificial intelligence has led to Avarai's integration in various other fruit and vegetable applications and gained one of the largest value contracts won by a British robotics company to date.



DR OLIVER PAYTON
CTO AND FOUNDING DIRECTOR OF BRISTOL NANO DYNAMICS AND FOUNDING DIRECTOR OF IMITEC



Dr Oliver Payton has developed and successfully commercialised two innovative technologies capable of mapping the invisible: the first enables the nano world to be observed with unparalleled ease and at unmatched speed; the second maps radioactive isotopes at high sensitivity over kilometre ranges. Both of these award-winning disruptive technologies have been exported all over the world.

Dr Payton's innovation journey started as a PhD student when he developed a new form of scanning probe microscope known as a high-speed atomic force microscope (HS-AFM), used in diverse areas of engineering ranging from nuclear systems to healthcare. This overcomes serious limitations of conventional machines and allows real-time observation of dynamic nanoscale processes or the mapping of nano and microstructures over millimetre-sized areas, thousands of times faster than alternative technologies. Dr Payton subsequently held an Academy Research Fellowship that allowed him to improve the microscope to the point of commercialisation. In 2015, he co-founded Bristol Nano Dynamics (BND) as a spinout from the University of Bristol, taking on the role of Chief Technology Officer.

Following a successful medical trial with collaborators in the US, BND's instrumentation is being developed for next-generation genome mapping. This can rapidly identify common blood and breast cancers and will be able to identify genetic diseases for which there are currently no tests.

Dr Payton has also developed a novel, remote radiation mapping system. This technology formed the basis of his second spinout company: ImiTec Ltd. The technology has since been used in several countries around the world, including over the Fukushima precinct and more recently around Chernobyl as well as on the UK's main nuclear decommissioning site, Sellafield.

ImiTec's radiation mapping technology can be mounted to crewed or uncrewed vehicles (ground or air based) and is capable of routinely searching nuclear sites for radiological threats, providing a first response to a nuclear emergency. More recently, ImiTec's Autonomous Airborne Radiation Monitoring System has been used to identify rare earth and precious metal mineral veins over a range of kilometres.

In 2015, Dr Payton was awarded the National Nuclear Laboratory Impact Award and a Royal Academy of Engineering ERA Foundation Award. He has advised the Department for Business, Energy and Industrial Strategy and the Government Office for Science on the next generation of radiological monitoring technologies.

FIXING TO FLY

In his time developing and testing helicopters, Philip Dunford FREng has undertaken most engineering roles, from working out their aerodynamics to seeing if they would float. As well as providing a string of entertaining, if sometimes hair-raising, anecdotes, he acquired a reputation as a troubleshooter who could bring programmes back on track with his systems approach to complex development programmes.

Had he achieved his schoolboy ambition, Philip Dunford FREng's aviation experience could have been limited to family holidays and flying to matches as a superstar football player. He attended trials at Southampton and Reading, before mechanical engineering intervened. While he remains a supporter of 'The Saints', his own sporting ambitions "didn't pan out", as he puts it. When his father urged him to "get a real job", Dunford looked locally. The family lived near to the Ministry of Defence aircraft testing site Boscombe Down, which is where Dunford's career started to take off.

Dunford began as an apprentice, learning how to keep aircraft flying for the Royal Air Force (RAF). It was a traditional apprenticeship that mixed practical and classroom work, including time spent in a workshop at Porton Down making his own tools. When his father's job took the family to Bedford, Dunford switched his apprenticeship to RAE (Royal Aircraft Establishment) Bedford to work towards a Higher National Certificate in Engineering.

Although he qualified to start working as a mechanic, Dunford wasn't ready to quit education. "As soon as I finished, for some reason, the government came up with this initiative to send who they considered eligible people who hadn't got their A levels to college," he says. Dunford opted for a degree in mechanical engineering at Brunel University. "They paid me a full salary to go to university for four years."

RETURNING TO THE AIR

Afterwards, Dunford wanted to "get back into airplanes". Now a bit older and wiser, he returned to Boscombe Down to work on helicopters in D Squadron. Soon after, he was singled out for the prestigious Empire Test Pilots' School (ETPS). Pilots from around the world came to the ETPS to learn to test different aircraft. Dunford was there to learn

When Dunford started his career, flight test engineers flew alongside pilots. As his career progressed, flying time gave way to developing new aircraft

to be a flight test engineer. "It was a big deal for me," he says.

Dunford describes his time at ETPS as "the hardest year of my life". He still has a class photo of his year group lined up in front of two fighter aircraft, where Dunford stands out as the one with a '70s haircut in the middle of a row of uniformed pilots. "There are not too many civilians in there," he jokes.

Back then, he explains, test engineers, known to the pilots as 'talking ballast', flew in the aircraft with the pilots. There was only one fixed-wing test engineer at ETPS that year. "So, I got to fly in all the fixed-wing aircraft and the helicopters, and I learned a lot about both. The test-pilot school was a really, really good experience."

Dunford's time at pilot school proved invaluable when he wanted to move on to new engineering challenges. "It set me up for the rest of my career," he explains. "It was the leverage that I needed to differentiate myself, because in those days not many engineers had done the course."

As he describes it, the test engineer's role with the UK Ministry of Defence was essentially to pick over the planemakers' work. "You were checking everything that the manufacturer had done first," Dunford explains. He wanted to be in at the beginning of the aviation development engineering process and to work on new aircraft. So, when Boeing's vertical take-off and landing (VERTOL) division in the US advertised for test engineers, Dunford applied. In a short time, Boeing flew him

The Chinook after the flight in freezing rain over Prince Edward Island, with the record-breaking amount of ice on it

to the US and offered him a job. Dunford credits his ETPS training with tipping the scales in his favour. "None of the engineers in their organisation had a test-pilot school background so it was kind of a shoo-in."

Dunford's first assignment with Boeing was to work with some previous colleagues at Boscombe Down. They conducted natural icing testing on the RAF Chinook in Shearwater, Canada. "We took the aircraft to Nova Scotia and, after a long flight in freezing rain over Prince Edward Island, we broke the record for the amount of ice grown on a helicopter in a single season." The Chinook tests went well. Dunford became an expert in helicopter icing, writing several papers on the subject and the UK still does icing tests in Nova Scotia. Unfortunately, his boss had stuck a Canadian Maple Leaf emblem on the front of the Chinook, which upset the RAF Wing Commander who had funded the tests. Following the officer's intervention, the maple leaf disappeared from the photos that appeared in the press.

Dunford can reel off similar anecdotes by the dozen, such as the time when food poisoning interrupted sonar trials with French Navy helicopters. Waiting for the sea to get suitably choppy, the test team went out for a seafood dinner that turned out to be bad. The two pilots got sick: one had to go to hospital. "We didn't get to fly that day, even though the seas were what we wanted." The tests, when finally completed, revealed worrying instabilities. "We had a big fight with the French test agency over our conclusions. In the end they actually changed the system based on our recommendations."

The next memorable incident was, he says, "some of the scariest tests I've done in my life". The tests, which were preceded by underwater escape training at HMS Vernon's infamous dunker, were in Lynx helicopters flying off Royal Navy ships HMS Coventry and HMS Avenger, in rough seas and high winds to develop operational flight envelopes for the Navy.

Dunford recalls another less scary "dunking" test. A Boeing 234 sank after it had to ditch in the North Sea. British Airways had bought six model 234 Chinooks to fly crews out to North Sea oil rigs. "The Civil Aviation Authority would not let the airplane fly until we could prove that we understood its floating capabilities." The engineers also had to show that they could seal the helicopter to prove that it wouldn't sink. "I had to calculate the buoyancy of the aircraft," he explains. Along with two pilots, "we dumped the airplane into the Delaware River and shut down the rotors to see how good our predictions were". Dunford had painted a 'water line' on the fuselage to show where he thought the helicopter would float. "It turned out to be pretty good." The crew successfully managed to restart the aircraft and take off from the water.

HYBRID AIRCRAFT

Dunford achieved his ambition of being involved in the engineering of a new aircraft when he joined the team working in the V-22 Osprey, a new kind of aircraft,

"I took the photographs of the first sea trial of the V-22. And they put my photographs on the cover of Aviation Week," says Dunford. Then Secretary of Defense, Dick Cheney was not happy that there was a successful test on the cover when he was trying to get rid of it. Dunford's bosses, on the other hand, were delighted

a hybrid between a helicopter and a fixed-wing aircraft [see 'Flying from the ground up']. The Osprey accounted for the next 15 years of Dunford's career, starting as a Flying Qualities Engineer, assessing the flying characteristics in the first simulations of the proposed aircraft. During that period Dunford had to deal with problems that threatened the whole Osprey programme. A lot hung on the V-22. It was one of the biggest development programmes in the US Department of Defense at the time.

It was while working on the V-22 that Dunford began to experience the role of politics in aircraft development. Always a controversial programme, with its roots in military failure, Dick Cheney, the then Secretary of Defense, was keen to cancel the Osprey, with its ever rising cost and technical challenges. "The development issues always made it a target for cancellation," says Dunford. The project faced a rocky political future, with various attempts to cancel the V-22.

His various roles on the V-22, rising to become Boeing's Program Manager on the joint venture, gave Dunford valuable experience in troubleshooting. His growing

QUICK Q&A

What inspired you to become an engineer?

The TSR 2 flying over my house in Amesbury, Wiltshire, during its brief test programme before cancellation.

What's your advice to budding engineers?

Get a technical integrity tattoo. Make systems engineering part of your modus operandi. Remember that the higher up the totem pole you go, the more your butt shows.

Best bit of the job now?

Working with young engineers during my consulting roles. This includes my daughter who is in her senior year at the Schreyer Honors College at Pennsylvania State University. Working on my *Execution Excellence* book.

Most admired historical engineer?

Isambard Kingdom Brunel; I went to his namesake university.

Do you have a favourite tool/tech gadget?

Slide rule. Still have mine from university.

Which engineering achievement couldn't you do without?

The helicopter. Both from a personal, a military, commercial, and humanitarian perspective.

Most impressive bit of engineering to look at?

Burj Khalifa, United Arab Emirates.

Overlooked engineering successes?

Sydney Darlington, Bell Labs – the inventor of the Darlington Pair (a multitransistor configuration) and the precursor to integrated circuits.

Dunford's first flight in the V-22 Osprey finally happened at the Farnborough Air Show in 2012. Again, Boeing had the Osprey on show, this time with the US Marine Corps in the driving seat. "They said to me, 'We're going to Boscombe Down to the test-pilot school, would you like to fly with us?'. We went up to the pilots' briefing room, had coffee and then went home. It was a great experience."

reputation on this front led to the role of Chief Operating Officer (COO) of Boeing military aircraft. "That really was a troubleshooting job." It wasn't his job to worry about the bottom line but to look at all of the business's programmes and their engineering issues. "I don't think you ever lose the engineering side of your character. It's always there." With a dozen or more aircraft and systems to play with, from fighters to helicopters and weapons systems, Dunford was flying all over the place.

This was another opportunity for Dunford to spread the word about his growing enthusiasm, developed on the V-22, for the role of systems thinking in managing large complex engineering ventures. "I was big on the systems engineering approach to development," he explains. "The army really embraced it when Boeing asked them to follow a very detailed systems engineering approach on the successful Apache Block III development programme."

The US Army was also in Dunford's sights when, as Vice President/General Manager of Boeing Rotorcraft, he served an unprecedented two terms as President and Chair of the American Helicopter Society. (It changed its name to the Vertical Flight Society in 2018.) One of the society's roles is to make the case for 'rotorcraft' in policy circles. As Chair, Dunford deployed his "bigger picture" approach to thinking about another challenge. He pointed out to the US Army that over the years the army hadn't commissioned the sort of clean drawing board exercise that led to the Osprey more than two decades earlier.

"They had an ever-decreasing number of new-start aircraft, and a lot of derivative modifications of aircraft that already existed and some of those aircraft were cancelled because of performance difficulties in the development programmes."

Dunford reckons that things have changed in the decade since he made that pitch. "I'm sure it's just not me that's driven this, but the army have changed that around now. They have initiated two exciting new helicopter programmes. They are actually doing all the things that the industry needed them to do, spending money on developing new capability."

SHARING EXPERTISE

It wasn't long before Dunford returned to Boscombe Down, this time as the guest speaker at the ETPS's graduation dinner, 30 years after he graduated. "I was very honoured to be asked to make that presentation."

Dunford has taken to lecturing pilots in general. For example, at the Society of Experimental Test Pilots in Los Angeles, he made the point that test pilots need to be more involved in the development process. "Pilots would just go fly, come back, and wait until they go fly again. They're engineers at heart. They have a lot of skill, they have a lot of engineering capability, they understand what it is that they're flying. I think there's room for them to be engaged in the early design of the aircraft." His message to pilots is, as he puts it, "be more of a geek and less of a jock".

As well as advising pilots, Dunford has made a point of mixing with students. When working on the V-22, he developed a course on it for engineering students at Caltech (the California Institute of Technology). "Telling them everything that we knew about an aeroplane that wasn't yet in production was quite an interesting situation. It was fun to do, especially at Caltech."

Dunford's career started in an era where the engineer's toolkit also included a slide rule. He is in awe of some of the tools available to today's students. Digital tools haven't just killed the slide rule, they have changed the whole development process. "The biggest change probably is the move to digital design and development, to the point now, where companies are building digital copies of their products, what they call digital twins of the product. The whole development cycle is now digitised and we're able to do things on the desk before you go fly." However, Dunford advises today's engineers to look beyond these tools. "They would also be wise to understand the principles of systems engineering."

FLYING FROM THE GROUND UP

Philip Dunford achieved his ambition to get stuck into developing a new aircraft from the ground up when he joined the engineering team building the V-22 Osprey. In his time on the aircraft, Dunford moved up the engineering hierarchy, taking on such roles as technology manager, flight test director, chief engineer and, finally, programme manager.

The V-22, a joint venture between Boeing's defence business and Bell Helicopter, was a new generation of VTOL aircraft. With its tilt rotors, the Osprey was the world's first hybrid, a cross between a helicopter and a fixed-wing aircraft.

The project grew out of a disastrous military mission in Iran. A hostage rescue went wrong, with several helicopter crashes. The US Marines wanted a more versatile VTOL aircraft for situations where neither helicopters nor fixed-wing aircraft were ideal. The aircraft's novel tiltrotor configuration means that the V-22 can take off vertically, tilt its rotors forward, and turn into a faster, fixed-wing machine with a longer range and higher operating ceiling.

Dunford joined the V-22 as flying qualities engineer. He worked on aerodynamics, propulsion and preflight wind tunnel testing, as well as working on the 'fly-by-wire' flight control system.

The tiltrotor arrangement created fresh engineering challenges. For example, the engineers had to deal with a complicated pattern of airflow around the V-22, with downwash from the rotors and the Rolls-Royce jet engines that powered the rotors. Then there was the not-so-small matter of two jet engines pointing downwards, with their hot exhaust threatening to damage the deck of any ship that they flew from. Dunford says of his role: "As the design progressed, I helped the aerodynamics and loads departments calculate the initial loads used to design the horizontal and vertical tail and worked with Northrop Grumman – the first producers of the horizontal tail."

The V-22 was a combination of subsystems that had to come together in the finished product. It was around this time that Dunford developed his thinking on how to manage complex engineering projects. Now recognised as a discipline in its own right, systems engineering deals with a programme in its entirety.

Dunford turned to systems engineering to deal with the high-profile problems, including fatal crashes, that had hit the V-22 in its early stages. In partnership with his NAVAIR (Naval Air Systems Command) counterpart, Dunford's approach to solving problems "included ensuring we followed a strict systems engineering approach to testing from start to finish, aggressive requirements management, risk and safety management, developing a 'fly before you fly' approach using extensive simulation and data analysis to support flight test, as well as extensive ground testing of the flight vehicle prior to flight".

As with many engineering projects, it was important to understand and measure what was going on. "We also micro-managed key metrics and knowledge points in the test programme, which eventually became the drivers of higher flight test productivity."

Dunford, by then in charge of the whole test programme, was gradually moving from hands-on engineering to a leadership role. Not only was he running large teams of engineers, he was also dealing with politicians. "Technically I was still engaged in [engineering], but I was one of the guys strategically guiding the programme."

When it came to dealing with what Dunford labels an "operational pause" – when the team had to spend a year or so recovering from a couple of fatal accidents – he had to immerse himself in the world of politics to explain the Osprey's engineering issues to government paymasters. Had that gone wrong, he explains, there was a chance that they would have cancelled the whole V-22 project.

Dunford knew that he had to come up with a strategy that would convince the US Department of Defense to continue the programme. He sat down and scribbled a return to flight strategy on a single sheet of paper. This eventually became the slide that explained the issues that faced this new type of aircraft to senior government personnel while offering a solution to the predicament.

It worked. The Osprey, which first flew in March 1989, eventually completed its first operational evaluation in 2005 when the Pentagon approved full production of what was the world's first production tiltrotor aircraft. With a fleet of more than 400 operated by the US Armed Forces, the Osprey V-22 has sold around the world and given rise to several variants, most recently the MV-22B version for the US Marines.

CAREER TIMELINE AND DISTINCTIONS

Apprentice mechanical engineer, **1968–1972**. Mechanical engineering, Brunel University, **1972–1976**. Flight test trials officer, Boscombe Down, **1976–1979**. Graduate flight test engineer, Empire Test Pilots School, **1977**. Joined Boeing Vertol (US), **1979**. Various roles on the V-22 Program, **1984–1998**. Director, Boeing Vehicle Systems and Technology, **1998–2000**. Fellow, American Helicopter Society, **2004**. Director Rotorcraft Engineering, **2004–2005**. V-22 Program Manager, **2005–2006**. Vice President Rotorcraft Operations, **2006–2008**. Vice President/General Manager, Boeing Rotorcraft, **2009–2010**. Fellow, Royal Aeronautical Society, **2010**. Chief Operating Officer, Boeing Military Aircraft, **2010–2015**. Honorary Fellow, American Helicopter Society, **2014**. Fellow, Royal Academy of Engineering, **2019**.

IMAGING THE PLASTIC RECYCLING PROCESS

The global problem of plastic waste shows little signs of abating and action is needed. Chemical engineer Dr Kit Windows-Yule's use of an innovative imaging technique, developed at the University of Birmingham, aims to improve the chemical process of breaking plastics down into oil so that they can be recycled and reused.

Dr Kit Windows-Yule is working with Recycling Technologies to analyse the internal workings of its fluidised-bed pyrolysis innovation, which uses extreme temperatures to break down plastic molecules for reuse

Plastic waste is one of the greatest challenges facing the world today. Every year, 32% of plastic packaging produced finds its way into our oceans, while 73% of beach litter worldwide is plastic. The problem is not only contained to oceans, and it affects humans, wildlife and their habitats. Yet only about 9% of plastic is recycled.

Dr Kit Windows-Yule, a nuclear physicist turned chemical engineer working as a senior lecturer at the University of Birmingham, wanted to do something to address this crisis. He has been working with Swindon-based Recycling Technologies (RT), which is developing a modular system designed to stop large amounts of plastic being transported from waste sites.

RT has developed a machine, the RT7000, that uses a method called pyrolysis – heating plastics at a high temperature in an oxygen-free environment so that the molecules that make up the plastic break up into smaller pieces, turning them back into something like the crude oil from which they were formed ('Processing the plastic problem', *Ingenia* 75). This means they can be used again to make 'good-as-new' plastic products, as well as clean, low-sulphur fuels.

RT already had a longstanding relationship with the University of Birmingham's School of Chemical Engineering. When Kit was awarded a Royal Academy of Engineering Industrial Fellowship in 2019, it allowed him to spend half his time working with the company, alongside lecturing at the university. He is helping RT analyse the internal dynamics of the RT7000 by using the positron emission particle tracking (PEPT) technique, developed by the University of Birmingham, to produce detailed imaging and study the 3D dynamics of what is going in the machine. He explains: "The PEPT technique was originally developed at the University of Birmingham by Professor David Parker and Dr Michael Hawkesworth, the former of whom I was lucky enough to have as my PhD supervisor. Since its inception in the late 1980s, PEPT has continued to be developed in the university's Positron Imaging Centre, an interdisciplinary centre founded in collaboration between the university's schools of physics and chemical engineering. In the early 2000s, the centre developed the world's first modular positron camera, which (unlike conventional systems) was both portable and could be reconfigured into effectively infinite different geometries, meaning it could image a wide range of scientific and industrial systems (including unusually shaped systems). Recent upgrades of the camera, led by the Positron Imaging Centre's Director, Professor Tzany Kokalova Wheldon, combined with

EYES ON THE INNOVATORS

***Ingenia* is keeping a close eye on the startups using their engineering know-how to disrupt the status quo.**

Yummy: **Xampla**'s pea-protein bioplastic featured in *The Times*. Although it may resemble clingfilm, it's edible so can be used to wrap stock cubes

Q-Bot, whose robots apply underfloor insulation with ease, received £1.6 million in investment, to help it keep more homes warm in the unprecedented winter to come novel algorithms and radioactive tracers developed within my research group, have enabled the work with RT to be realised."

INNER WORKINGS

The technology is a portable, modular positron imaging camera, which allows researchers to 'see inside' industrial systems and understand their inner dynamics. "It carries a big advantage over, for example, X-ray imaging in that it uses highly penetrating gamma rays (as opposed to lower-energy X-rays), which means that we can even see through materials such as steel and titanium," explains Kit. "This makes it ideal for imaging industrial systems, which are often constructed from such materials." However, the innovation is that it is both portable and modular, consisting of a lot of individual blocks that can be built, Lego-style, to suit various industrial geometries.

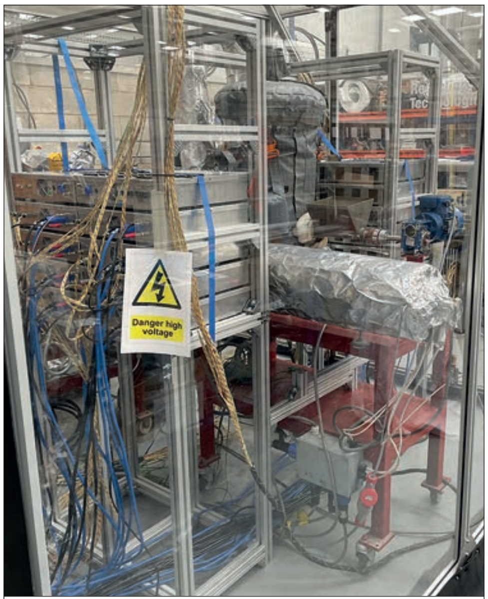
RT's challenge was that it did not previously know how the plastics behaved once fed into the RT7000 system: for example, how long do they stay as solids? How quickly do they melt and evaporate? Are they spread evenly (and thus efficiently) throughout the system? "By using our positron imaging methods, we were able to directly image these processes for the first time ever," adds Kit, "and provide valuable information regarding how their systems should be operated to ensure maximum efficiency."

Kit secured follow-on funding including a £440,000 EPSRC New Investigator Award, a Royal Society Research Grant, and an Academy-funded Proof of Concept Award. This allowed him to develop extra tools and acquire necessary permits to track individual particles and model the internal dynamics of the process, to measure the influence of gas flow rates, distributor design, and the size and shape of plastic inputs. "We used gamma radiation to actually see inside their [RT's] solid steel reactor and image the processing, melting and devolatilisation of plastics as they are broken down into their basic chemical components for recycling. This is the first time that this kind of imaging has ever been done on-site in an active industrial facility." Essentially, Kit and RT were able to better understand how the system operates, and how the process can be improved and optimised for better energy efficiency and more careful control of the end products.

The imaging work is supported by numerical modelling techniques such as coupled computational fluid dynamics and discrete element method (CFD-DEM) simulations and Barracuda MP-PIC simulations, which allow true-to-life simulation of the systems of interest. The application of numerical simulations allows not only deeper insight, but also allows Kit to improve, expedite, and reduce the financial impact of optimisation processes – he can come up with and test new ideas for different geometries or operating conditions, for example, using only a computer. Promising ideas can then be tested at the lab scale using conventional PEPT and, if successful, ultimately implemented in the real system.

PORTABLE PROCESSES

"Conventional, lab-based PEPT is already widely used for exploring and optimising diverse process equipment in the agriculture, chemical, food, green energy, pharmaceutical, and personal care sectors (among others)," Kit says. "As such, there is significant potential value to the use of on-site PEPT in these sectors, especially for pilot-scale equipment that cannot be feasibly transported to Birmingham, or for continuous processes where the imaging of individual components of the process in isolation from up- and down-stream processes would not be meaningful." In the coming years, the intention is to set up a spin-out company for such purposes. "Our modular camera can be applied to anything from pharmaceutical secondary manufacture and chemical processing to biofuels production, or even the development of personal care products like shampoo and conditioner."



The modular PEPT camera on site

The modular nature of the RT system is also important, as all major components can be individually transported on a single flatbed truck. Firstly, it means that recycling centres can easily be set up across the country; this decentralised approach removes the need to transport plastic over long distances across the country to a single, centralised facility, and significantly reduces the greenhouse gases emissions caused by these long journeys. Secondly, the modular approach means that recycling facilities can be easily set up in areas with little infrastructure, making them suitable for use in low-income countries where the plastic waste crisis is most acutely felt. Since the recycling process converts plastic into pseudo-crude oil, it also 'monetises' plastic waste, turning it from a waste product into a resource with financial value, meaning that the arrival of these machines in such countries carry the potential not only to create jobs, but an entirely new economy.

Having been awarded his second Industrial Fellowship in 2021 to continue working with RT, Kit hopes that he will be able to contribute to the further development of this technology that, if widely adopted, could provide transformative in the fight against plastic waste.

Strike a pose: transparency software company **Provenance** shared wise words on greenwashing in the beauty industry in *Vogue Business*

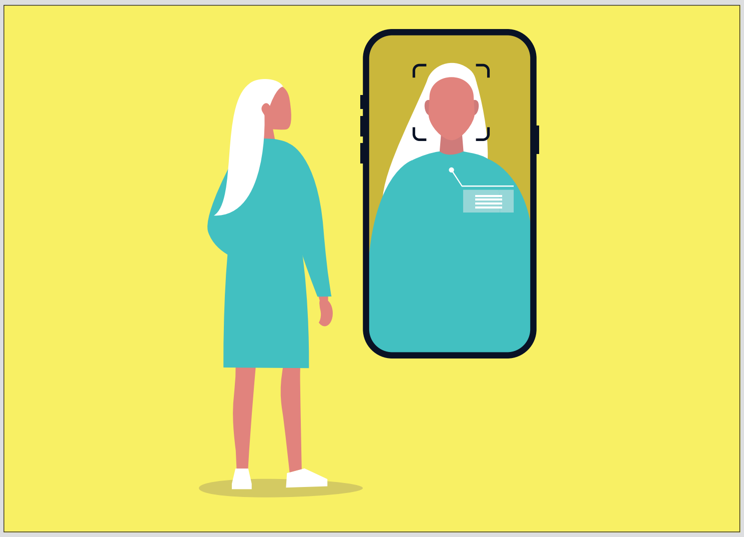
BBC World News showed how **mOm Incubators'** Essential Incubator is keeping newborns warm during air raids in the basement of a Kyiv children's hospital

Low-carbon brickmaker **Kenoteq** has been shortlisted for Dezeen's sustainability awards. Its K-Briq™ is made from 90% construction waste

HOW DOES THAT WORK?

FACE FILTERS

It started with face swaps, flower crowns and appended dog ears. Now, all manner of transformative sorcery is just a tap away. You can swap your gender or your age, or more worryingly, even subtly distort your features to meet today's ever-narrower beauty standards.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Dig into any of the biggest social media apps and you'll find an array of filters that can transform the input from your phone's front camera. These augmented reality (AR) effects can change a person's appearance, or that of their background, using computer vision and image processing models that perform real-time video modifications.

Among the millions of filters available, you'll find all sorts. You can accessorise with some glasses or throw in a few sparkles, as if you've been doused in glitter. Other filters are limited only by their creators' imaginations and range from the ridiculous to the fantastical. The classics include the face, age or gender swap; appended animal ears, or the Pixar version of you. But you can also, if you like, freakishly distort your features, or see what it would look like if your face were plastered onto the body of a giant prawn. Or instead of the boring wall behind you, why not take on the lo-fi graphics of a noughties music video – using the very same background subtraction technology popularised by Zoom during the pandemic?

Face filters rely on computer vision and image processing models that can modify a video feed in real time. Central to the process is a facial detection algorithm, such as the Viola-Jones algorithm (for more on facial recognition technology, see *Ingenia* 79). This algorithm works out differences in contrast between portions of an image to detect the edges of the features. For example, as any portrait artist knows, the eye sockets, sides of the nose and lower lip are darker than the upper lip, bridge of the nose and middle of the forehead. If the algorithm finds enough of these features, it can detect a face.

Having detected the facial features, the software then aligns a statistical model of the face with to face in question using machine learning. Called an active shape model, this is derived from hundreds of thousands of facial images, on which people have marked the borders of features. A mesh representing the 'average face' from this model is then scaled and aligned with the user's face, with adjustments made where it doesn't fit perfectly.

This mesh is where the magic happens. Using special software, it can be distorted, or have accessories attached to it, or have colour changes applied to segments of it (such as the eyes). Importantly, the mesh and any programmed alterations to it must move along in real time with the video of your face, for a smooth viewing experience. But this tracking isn't quite perfect yet, as can be seen when people turn their heads to the side, as effects can disappear. Plus, in some cases, the algorithms must account for occlusion. This refers to what happens say, when a hat is seen from a three-quarter profile: the head will block the back of the hat from view. So, for a hat filter, the part of the animation behind the head must be subtracted.

One concern about filters that has been increasingly highlighted is the beauty filter. Although they rely on distortion too, the distortion is so subtle you might not immediately notice it if you saw it on someone else's photo. However, the effects are worrying: noses or jawlines can be slimmed down, skin can be smoothed, eyes and lips enlarged, and eyelashes lengthened to achieve a so-called 'Instagram face' – a Eurocentric standard of beauty often achieved with cosmetic procedures.

What's more, not all 'beauty' filters are labelled as such – sometimes a hat filter might also slim down your nose. All of this adds up to a troubling phenomenon that has been dubbed in the media as 'filter dysmorphia', a new version of an old problem to which some young people are particularly susceptible. This is an issue tech companies will need to consider carefully if filters continue their trajectory of popularity.

Beyond the uses purely for social media, brands are developing filters allowing people to try on clothing, accessories, jewellery, and makeup, or see what a piece of furniture could look like at home. While these haven't gone mainstream yet, in the next few years, you could well be investing in your next pair of glasses without ever seeing them in person.


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