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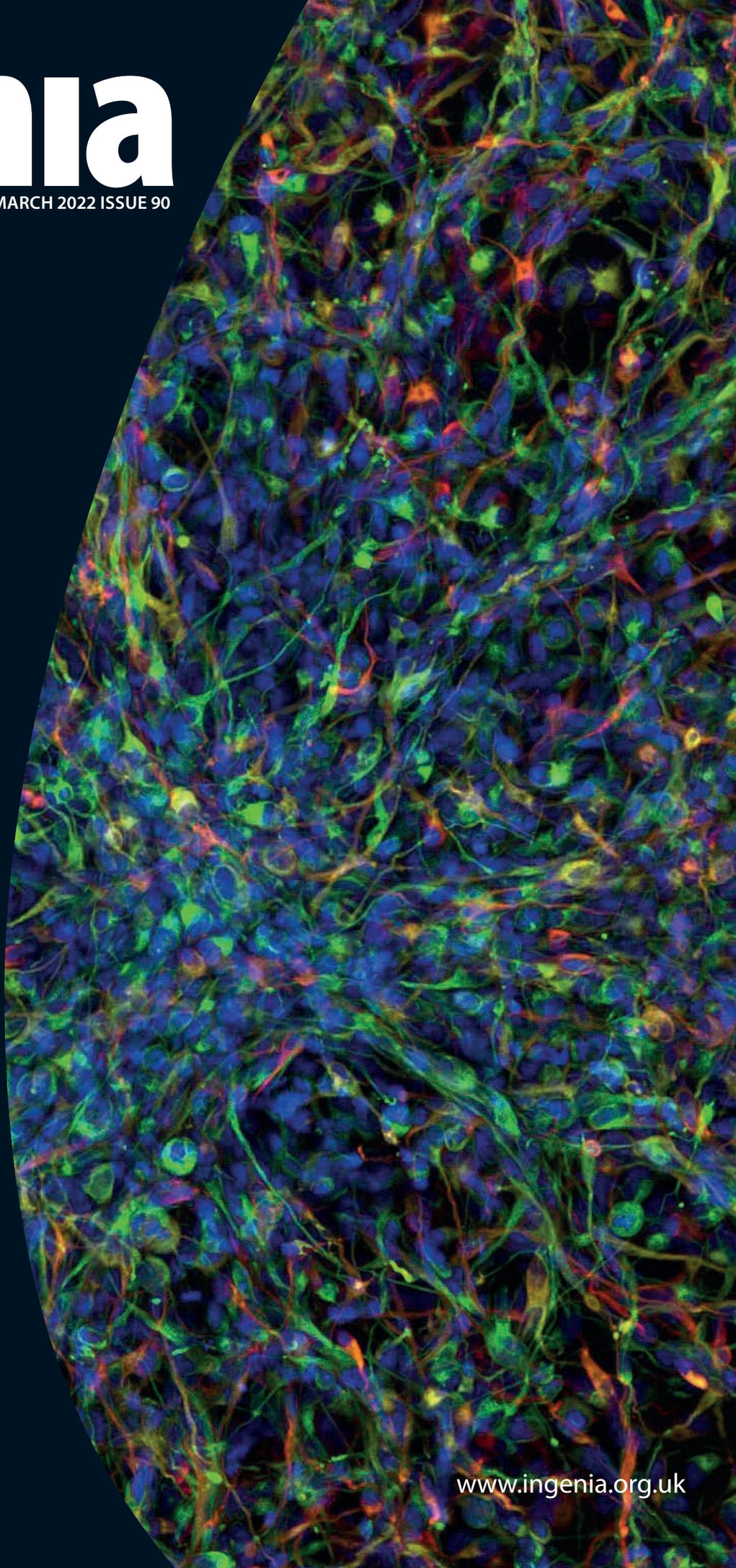
MARCH 2022 ISSUE 90

PREVENTING HIDDEN CORROSION

COVID LAB-ON-A-CHIP

ACCURATE LOCATION MAPPING

MAKING ORGANS IN MINIATURE



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Royal Academy of Engineering, Prince Philip House, 3 Carlton House Terrace
London SW1Y 5DG
Tel: 020 7766 0600 | Website: www.raeng.org.uk Email: ingenia@raeng.org.uk
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Editor-in-Chief
Faith Wainwright MBE FREng

Deputy Editor-in-Chief
Professor David Delpy CBE FREng

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Front cover

Highly invasive human paediatric brain tumour derived cells. © Valeria Molinari, Louise Howell, Maria Vinci, Katy Taylor and Chris Jones, Institute of Cancer Research

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WELCOME

Engineers are creative and turn ideas into practical solutions. Our story about robotic vacuum cleaners ('How does that work?' page 36) beautifully illustrates, on the one hand, combining different technologies while, on the other, deeply understanding the practical challenges of tidying rooms remotely. Product design and constant evolution of ideas have ensured that this previously sci-fi idea is now an increasingly popular and useful answer to keeping rooms clean.

Dr Youmna Mouhamad's quest to transform the experience of detangling hair from one of pain to joy ('The afro comb inspired by printing', page 35) is also a story of a passion to solve a problem. To do this, she dug deep into the latest technologies and worked with others to not only develop an exciting new product, but to also inspire others to have confidence in their ideas.

Creativity combined with a passion for making things better and easier for society motivates engineers in every field. To speed up the development of drugs and at the same time make them much more effective, engineers are translating micro-technologies used in computer chips to be able to emulate the real behaviour of cells in our bodies ('Life on a chip', page 19). Such advances in bioengineering need close working with biologists, physicists and chemists, and this artificial modelling could lead to the ability to run tests on a 'mini-me' chip before drugs ever reach a patient.

These exciting solutions are excellent illustrations of how engineers combine technical understanding with creative skills to tackle all kinds of challenges. We want to hear about the exciting engineering that you'd like to know about, so please get in touch at ingenia@raeng.org.uk, let us know on Twitter using #IngeniaMag, and fill out our reader survey (QR code, left) – your feedback helps inform our content and ensure *Ingenia* continues to bring you inspiring stories and insights.

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

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IN BRIEF

IN BRIEF

WORLD'S STRONGEST PERMANENT MAGNET INNOVATOR WINS 2022 QEPRIZE

The neodymium magnet is critical for clean technologies: it is a key component of the electrical generators in wind turbines © Hugo Delauney/Unsplash

On 1 February, the 2022 Queen Elizabeth Prize for Engineering (QEPrize) was awarded for the development of the world's most powerful permanent magnet, which has been an integral component of clean technologies such as electric vehicles and wind turbines. The technology underpins everyday life as we know it – and for the most part, without many of us even knowing it's there.

Japan's Dr Masato Sagawa was awarded the prize for his pioneering work on the discovery, development and global commercialisation of the sintered Neodymium-Iron-Boron permanent magnet, also known as the neodymium magnet.

Dr Sagawa's breakthrough innovation was replacing the scarce and expensive elements cobalt and samarium with more abundant and cheaper iron and neodymium. He also introduced boron to improve the magnetic properties, which was the first step in delivering high performance to a mass market.

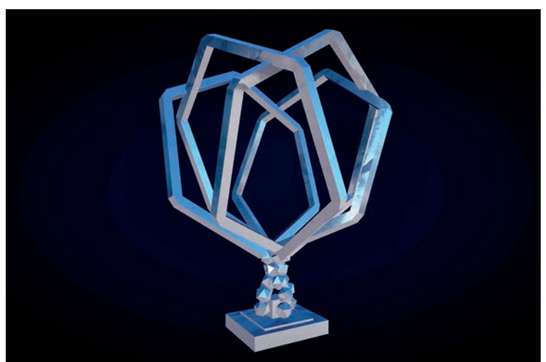
However, the magnet demagnetised at high temperatures – a real problem in extremely hot conditions, such as car engines. To overcome this problem, Dr Sagawa led the R&D in the late 1980s and early 1990s to overcome this problem, notably by adding dysprosium to improve heat resistance. Thanks to this work, high-volume manufacturing techniques were developed, resulting in a new magnet that almost doubled the performance of the previous best.

The magnet has a significant advantage in high-efficiency and high-torque density applications, such as motors and generators for electric vehicles and wind turbines. They are also used in a wide range of other applications, from robots to automation systems and domestic appliances.

This year's *Create the Trophy* competition winner, announced on the same day, was Anshika Agarwal, a 17-year-old content writer from India. Anshika's design features interwoven hexagons, representing the global connections created by modern technology. Open to those aged between 14 and 24 around the world, competitors enter innovative trophy designs to be presented to the winners of the QEPrize.

Dr Sagawa will be formally honoured at the QEPrize presentation ceremony later this year, where he will receive £500,000 and the unique trophy.

www.qeprize.org



The winning design for the 2022 Create the Trophy competition by Anshika Agarwal

NORTHEAST GIGAFACTORY GIVEN THE GO AHEAD

The UK government has awarded startup Britishvolt, a manufacturer of car batteries, a grant of £100 million that will help fund a full-scale Gigaplant in Blyth, Northumberland. Britishvolt says this should create around 3,000 highly skilled jobs in Northumberland, plus over 5,000 jobs indirectly in the wider supply chain. Production is scheduled to begin in 2024 and to reach full capacity in 2028.

A architectural rendering of the Britishvolt electric vehicle battery plant, due to be built in Northumberland © Britishvolt

The company has also announced several complementary initiatives since the news of the Gigaplant. It is pairing up with mining company Glencore to address a contentious issue: end of life for electric vehicle batteries. The collaboration aims to set up a world-leading recycling centre to recover critical metals needed for the energy transition into the battery supply chain.

Electric vehicles are becoming an increasingly important piece of the transition to net zero. Sales in the UK are booming, with almost 200,000 sold last year across the country. For the UK's car industry to meet the continuing needs of the transition, local battery manufacturers will be vitally necessary to secure a manufacturing presence in the UK and supply power to future vehicles.

High-performance car manufacturer Lotus is also getting in on the action, partnering with Britishvolt to develop a Lotus electric vehicle. The hope is that as with Formula 1, high performance R&D will ultimately have beneficial trickle-down effects for more affordable batteries and electric vehicles.

PUTTING ETHICS AT THE HEART OF ENGINEERING

On 24 February, leading engineers set out plans to embed a more ethical culture at the heart of the UK's engineering profession, starting with a new report and tools for higher education students from the Royal Academy of Engineering and the Engineering Professors' Council.

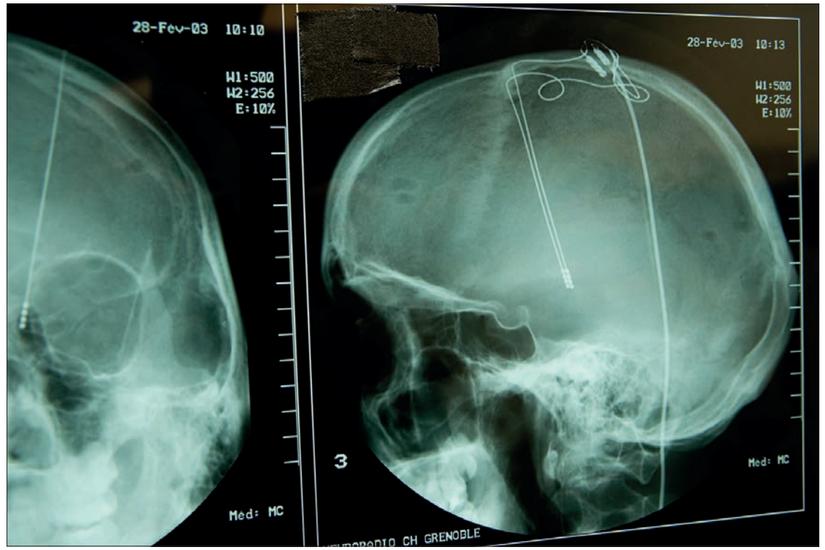
Engineers make critical decisions all the time – about everything from the physical infrastructure that surrounds us, to the climate, the digital fabric of our lives and how information flows through it, and much more besides. Where the wrong outcomes are prioritised, catastrophic results can follow, with the Grenfell Tower tragedy one particularly serious example. Countless other instances show where engineers could have better implemented ethics in decision-making, whether it's crash test dummies based on male drivers that leave women more at risk in car accidents; or how algorithms and search engines have further embedded pre-existing structural inequalities.

As part of the work, the committee has written a report recommending ways to help improve awareness of ethical issues in the profession and help engineers to deal with and call out bad practice. It also designed

12 case studies for undergraduate students to explore scenarios where ethics could relate to their own everyday working lives, including considering trade-offs in the energy transition to how new software could misuse personal data.

To read the report and case studies and watch the launch event, please visit **www.raeng.org.uk/ethics**

BRAIN STIMULATOR IMPLANTED IN PATIENTS FOR THE FIRST TIME



A group of engineers and neuroscientists from the University of Oxford have worked with Bristol-based bioelectronics startup Bioinduction on a clinical trial to implant a brain stimulator in patients for the first time.

Led by Professor Tim Denison, a Royal Academy of Engineering Chair in Emerging Technologies, the trial has seen five patients with multiple system atrophy (MSA) have the Picostim™-DyNeuMo pacemaker implanted into their brains. These devices, which can ease symptoms, are inserted deep into the brain to stimulate the tissue with electrical signals.

MSA is a rare, degenerative neurological disorder that shares many similarities with Parkinson's disease. The team's research will explore the role of circadian rhythms, motion and different brain signals in the disease and its treatment. It also aims to identify biomarkers that signify the state of the disease, and how these vary throughout the day/night cycle. Ultimately, the plan is to develop stimulation patterns that optimise symptom management and improve sleep.

Along with the trials studying MSA, the team is also preparing separate trials to study how the technology can be used for post-stroke chronic pain, epilepsy and disorders of consciousness.

WE WANT TO HEAR FROM YOU

As *Ingenia* looks towards the future and plans to increase its presence online, we want you to share your thoughts on the magazine – what you like, what you don't like, what digital content you'd like to see, your favourite parts of the magazine, and more.

Your feedback helps inform the continued development of *Ingenia*, so we'd like to hear what you think about its content and what you're interested in reading about. Are there any exciting engineers or engineering projects you'd like us to cover? Any areas of engineering that don't get enough attention?

We'd also really like to know how it's used in schools and colleges so that we can develop content that's useful for teachers and that will help students make choices about their future study and career options.

So that we can continue to bring you exciting, inspiring stories that cover the creativity, variety and breadth of engineering, please scan the QR code (right) and complete our anonymous reader survey.

To help us develop insight into how different groups of readers experience *Ingenia*, it would be really useful if you could also complete as many of the 'about you' questions as possible

Thank you for your support.

GET INVOLVED IN ENGINEERING

EDINBURGH SCIENCE FESTIVAL

9 to 24 April

Edinburgh Science Festival is back: from the 9 to 24 April, venues across the city will host experiences for all ages, from interactive exhibitions to workshops, performances, screenings, and evening talks and discussions. This year's theme is 'Revolutions' and will explore multiple senses of the word: the power of circles, lifecycles, and revolutionary technologies and approaches to tackling global problems, from health to the climate crisis.

www.sciencefestival.co.uk/festival

BRITISH SCIENCE WEEK

11 to 20 March

This year's British Science Week is themed 'Growth': look out for events happening in your area or plan your own activities with the packs available online. You'll be guided through making a terrarium, designing an aeroplane or building a gentoo penguins' nest. An annual poster competition is also open until 15 April for ages 3 to 14.

www.britishscienceweek.org/plan-your-activities/poster-competition

CREATE THE FUTURE PODCAST

All podcast providers

The first few episodes of season three of *Create the Future* are now live. Opening the series is award-winning mechanical engineer Sonam Wangchuk, discussing the origins of his famous Ice Stupa project and ongoing mission to inspire global change in the face of multiple climate crises. Other episodes include the winner of the 2022 QEPrize, Dr Masato Sagawa, and pioneering audio engineer Leslie Gaston-Bird.

https://qeprize.org/podcasts

FOR YOUR INSPIRATION: POWERING OUR SUSTAINABLE FUTURE

6.00pm, 18 March

Royal Institution, London

Join researchers working at the Faraday Institution to find out how new breakthroughs in battery technology will help the world meet global challenges such as climate change, air pollution and sustainable jobs.

www.rigb.org/whats-on/events-2022/march/family-for-your-inspiration-powering-our-sustain

THE FUTURE OF LIFE ON EARTH

1.00pm, 9 May

Barnard's Inn Hall, London, or online

Award-winning author, science communicator, and cosmology and data science expert Roberto Trotta reflects on what's in store for life on our pale blue dot, Earth.

www.gresham.ac.uk/lectures-and-events/future-life

FOOTBALL: DESIGNING THE BEAUTIFUL GAME

From 8 April

Design Museum, London

It's been estimated that half the world's population – 3.5 billion people – watched the World Cup in 2018. But what innovations have made football what it is today? How were the world's most significant stadiums master-planned? What innovative materials are used to make today's boots? Learn about all this and more and see a pair of Lionel Messi's very own boots at the Design Museum.

https://designmuseum.org/exhibitions/football-designing-the-beautiful-game

NEW SCIENTIST LIVE

12 to 14 March

Manchester Central Convention Centre, or online

Manchester's Central Convention Centre will welcome over 9,000 visitors, 40 speakers and 30 exhibitors in person for on-stage talks and hands-on demonstrations. Saturday and Sunday of the event are open to everyone, while Monday is focused on schools and learners at home.

live.newscientist.com

HOW I GOT HERE

HOW I GOT HERE

Q&A

KATE TODD-DAVIS
MANUFACTURING ENGINEERING APPRENTICE

Apprentice Kate Todd-Davis followed her passion for aerospace and automotive engineering to Rolls-Royce – and gained a degree in manufacturing technology from the University of Sheffield along the way.

WHY DID YOU FIRST BECOME INTERESTED IN SCIENCE/ ENGINEERING?

I've had an inquisitive mind from a young age, always questioning how and why things work, but I wasn't really exposed to engineering until I was in secondary school. When I was 14, I visited the Santa Pod Raceway and witnessed the astounding speed of the drag cars – I had to understand how they managed to travel so fast. Since then, my passion for aerospace and automotive engineering has grown and I've continued to fuel my curiosity by working for Rolls-Royce.

HOW DID YOU GET TO WHERE YOU ARE NOW?

After studying triple science, maths and further maths at GCSE, I studied A levels in maths, physics and chemistry. When I was at college, I completed work experience at Caterpillar and was accepted onto the EDF Energy Mentoring Scheme at the Hartlepool Nuclear Power Station. I applied to Newcastle University to study a master's degree in design and manufacturing engineering as well as the Manufacturing Engineering Degree Apprenticeship through Rolls-Royce. Although I was accepted for both, I knew that I wanted to follow the apprenticeship route.

I graduated with a first-class honours degree in manufacturing technology from the University of Sheffield's Advanced Manufacturing Research Centre (AMRC) Training Centre, while gaining invaluable industry experience at the Rolls-Royce facility in Washington, UK. I've also completed a Level 2 NVQ in fundamental engineering and am now working towards a Level 4 NVQ in engineering and advanced manufacturing – both delivered by the Sunderland Engineering Training Association.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

Getting a first in my degree has been my greatest academic achievement so far, and I was recently awarded 'Highly Commended Degree Apprentice of the Year 2021' through the National Apprenticeship Service. I was also named 'Apprentice of the Year 2021' and 'Degree Apprentice of the Year 2021' through the University of Sheffield AMRC Training Centre, where I studied towards my degree.

I've also been involved with the recently set up women in science and engineering group onsite. This has been a fantastic networking opportunity and has helped me appreciate the challenges my colleagues who are women have faced during their careers. Hearing their stories has motivated me to be more ambitious and hopefully encourage more women to pursue a career in engineering through my involvement in local STEM events.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

I love being given the opportunity to constantly learn, develop and challenge current ways of working. Being at Rolls-Royce has exposed me to a variety of experienced and passionate colleagues who have mentored and supported me to achieve my potential. Seeing their achievements and progression within the company has further motivated and inspired me to maintain a strong work ethic and support my future ambitions.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

On a day-to-day basis I spend most of my time on CAD/CAM software, updating models and processes and analysing data. I also write and update technical instructions, which are used by the inspectors and operators on the shop floor. I am currently completing a Lean Six Sigma Green Belt and Level 4 NVQ qualification, while volunteering as a North East Young Apprentice Ambassador.

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

Anyone, at any age, considering a career in engineering should go for it! It's such a diverse and captivating industry, and the opportunities are vast. I would also encourage considering an apprenticeship. I think it's the most logical route to success, as it provides you with both work experience and technical knowledge.

WHAT'S NEXT FOR YOU?

In the next few years, I'd like to be in a full-time position at Rolls-Royce. I want to continue my involvement in digital aspects of engineering as I think this is the future of the company, with the improved process capability and more efficient ways of work that will become possible. From an academic perspective, I'd also like to complete a master's degree to continue my professional development.

QUICK-FIRE FACTS

Age: **21**

Qualifications: **BEng (Hons) in manufacturing technology, University of Sheffield AMRC Training Centre**

Biggest engineering inspiration: **Katharine Parsons, an engineer who advocated for women in the field and co-founded the Women's Engineering Society in 1919**

Most-used technology: **Spotify – music helps me to stay focused and motivated**

Three words that describe you: **Driven, ambitious, inquisitive**

OPINION

OPINION

BETTER BUILDINGS NEED A BREATH OF FRESH AIR

As the world adapts to living with COVID-19, buildings such as schools, hospitals and office blocks should be well ventilated to reduce risk of transmission. But how can we achieve this while keeping warm and lowering energy consumption? Dr Shaun Fitzgerald OBE FREng, Director of Research in the Centre for Climate Repair at the University of Cambridge, says that good ventilation doesn't mean throwing open all the windows, and that existing buildings need to be better regulated and monitored to ensure they can be warm, safe and climate friendly.

COVID-19 has wreaked havoc on the world in so many devastating ways over the last two years. Importantly, researchers have discovered that ventilation of buildings can effectively reduce the risk of SARS-CoV-2 virus transmission. In 2021, Sir Patrick Vallance KBE FRS, the government's Chief Scientific Adviser, commissioned a report from the Royal Academy of Engineering on how to reduce the risk of infection indoors, in which experts say the importance of ventilation is too often "neglected" and there is an "urgent need" to improve it.

The *Infection Resilient Environments* report recommends that multiple occupancy spaces should be well ventilated to minimise the build-up of virus if infectious persons are present. Additionally, the benefits of a well-ventilated space go beyond helping reduce the risk of SARS-CoV-2 transmission; higher ventilation rates can lead to enhanced levels of concentration, reduced likelihood of mould growth, and reduced risk of transmission of other airborne pathogens.

While it is easier to ventilate buildings by opening windows during the spring and summer, there are challenges in delivering the appropriate amount of ventilation in colder weather – especially with a focus on reducing buildings' energy consumption and keeping warm.

Heat loss through conduction, uncontrolled air leakage and radiation are the biggest issues engineers face in reducing energy use in buildings. Improving insulation levels helps to reduce the heat lost by conduction through the building fabric. However, action is needed to not only improve panels' insulation, but also the quality of the areas where they are joined. Additionally, sealing gaps in the building fabric means that when a building is empty, it will not leak out the warm air from the previous day or occupied period. This helps keep the building warm and reduces the need for a heating system to preheat the building before re-occupation. Finally, installing coatings on windows or foil-backed insulation in the attic space can help reduce heat loss by radiation.

Once the building fabric has been upgraded to a good level, when the building is occupied the space can be well ventilated, even in cold weather, without excessive energy use. This is because natural heat gains within the space can often be sufficient to maintain the interior at a comfortable 21°C and provide ventilation without extra heating or a heat recovery scheme, even when the external temperature drops to 5°C. The combined heat gains from IT equipment, lighting, solar, and the occupants themselves are considerable. If the ventilation system is designed to exploit these heat gains by premixing the incoming cold air with warm room air, adequate levels of ventilation can be provided without cold draughts.

Unfortunately, many existing buildings have poorly maintained ventilation systems. For example, if a building has opening windows, not all the windows may in fact work: many windows at lower levels that are easily accessed by occupants are better maintained than those at higher levels. While losing a few opening windows isn't a problem in the spring or autumn, it can be a problem in winter if they are the top ones. Cracking open all the high-level windows a small amount provides good levels of ventilation but without cold draughts – the incoming cold fresh air can mix with the air in the space and be warmed before it hits the nearest occupant. This means that radiators should not need to be turned up to alleviate cold draughts. Without the high-level windows, it will be too cold to provide the same level of ventilation directly via low level windows. Occupants will therefore close them, which should be avoided from a health perspective now. Monitoring of buildings to check whether adequate levels of fresh air are in fact being provided is extremely variable – buildings with controlled ventilation systems and CO_2 sensors in occupied spaces can more easily provide appropriate levels of fresh air. Buildings that have people together for extended periods of time that rely on manual openings are more challenging, as was highlighted in a study of an outbreak in a restaurant in Wuhan. For example, can restaurant visitors be assured of the level of fresh air at their table? There are health and safety issues in food preparation in kitchens, but it is a different situation in the public area. Now that an environment's air quality and its role in creating safer spaces has been brought into sharper focus, government and professional bodies will need to develop further regulations and guidance and communicate these clearly and consistently. More importantly, architects, engineers, and building owners and operators must ensure these are applied.

Finally, engineers must find a balance in winter between reducing the risk of SARS-CoV-2 transmission to an acceptable level and keeping energy use low. Increased levels of ventilation reduce the risk of transmission, but once these are considered reasonable, the benefits from reducing the risk of transmission decrease for each litre per second per person of outdoor air provided – and energy costs continue to rise. Therefore, our focus should be on addressing buildings that don't meet current building regulation standards for ventilation as these buildings arguably present the greatest risk for transmission. They are also likely to consume the most energy as a result of poor building fabric and systems. There is a role for different controlled ventilation systems ranging from natural ventilation to full heat recovery schemes. In addition, high efficiency particulate air (HEPA) filters or ultraviolet light (UVC) systems can help reduce infection risks in locations where good ventilation is difficult to achieve. However, the benefits of using other kinds of air cleaning devices are less clear.

The pandemic has revealed flaws in the way in which we design, manage and operate buildings. Unless they are addressed, these could disrupt management of this and future pandemics, impose high financial and health costs on society, and constrain our ability to address other challenges such as climate change. Well-designed and maintained ventilation systems can help overcome the challenges that COVID-19 poses and contribute to the transition to zero-carbon buildings. As the *Infection Resilient Environments* report notes: "government policy on net zero must be developed in a way that is consistent with priorities around indoor air quality and making buildings resilient to infection." It is not a choice between COVID-19 resilient and climate-friendly buildings; it is a case of improving buildings to meet both goals.

BIOGRAPHY

Dr Shaun Fitzgerald OBE FREng is Director of Research in the Centre for Climate Repair at the University of Cambridge. His academic research on ventilation led to him founding and leading Breathing Buildings from 2006 to 2018. He is a member of the SAGE Environmental Modelling Group, one of the authors of the Chartered Institution of Building Services Engineers Emerging from Lockdown series, and currently part of the AIRBODS research team.

© Unsplash/NASA

SUPERCHARGING GPS PRECISION

Did you know?

- At any given time, at least four GPS satellites are visible in the sky anywhere on Earth
- GPS positioning is less accurate in cities because the signals are reflected by tall buildings in 'urban canyons'
- New technologies could boost accuracy and even help us navigate indoors

Satellite-based positioning technologies have taken over the world since their inception during the Space Race. Although they can now pinpoint a location to within a few metres outdoors, they still suffer from unsolved problems, such as drift near obstructions like tall buildings, bridges and trees. Now, companies like Focal Point Positioning (FocalPoint) are using sensor fusion and signal processing technology to overcome these problems and find new applications for the technology.

It's hard to imagine life without GPS. Instead of poring over a map and writing down directions, we grab a postcode and plan a journey at the touch of a button on a smartphone or satnav. We can watch a taxi driver or takeaway as it approaches or watch ourselves trundle towards an e-scooter around the corner. Of course, it goes beyond our everyday conveniences: thanks to GPS, paramedics can pinpoint a person in need of medical assistance down to a few metres. Air traffic controllers at airports can track and monitor inbound planes to prevent delays and collisions. Ships can be carefully guided through the busy English Channel. Conservationists can track animals and their migratory patterns, from flocks of swifts to herds of bison.

So how does this technology work, and what possibilities could open up if it was to become even better than it already is?

GPS AND GNSS

Satellite-based positioning was conceived in the days of the Sputnik I satellite and the Space Race. When Sputnik I was launched, Soviet engineers equipped it with a radio emitter to allow people on Earth to track the satellite's launch and orbit. Scientists knew that the frequency of these signals dropped slightly as the satellite passed the receiving station, thanks to the Doppler Effect (which describes the difference between the frequency of a wave when it leaves a source compared to when it reaches an observer). They then realised that this frequency data could be used to predict the satellite's orbit, and furthermore, that they could use this same principle to calculate the position of an object on Earth, and so GPS was born.

GPS stands for Global Positioning System technology and is one of the better-known Global Navigation Satellite Systems (GNSS). The overarching term GNSS encompasses different satellite-based positioning, navigation and timing systems used across the globe:

- GPS, operated by the US
- GLONASS (Global Navigation Satellite System), operated by the Russian Federation
- Galileo, operated by the EU
- BeiDou Navigation Satellite System (BDS), operated by China.

All GNSS are, at their core, just atomic clocks in space, ticking. The messages we receive from the satellites tell us the time from these incredibly precise clocks, along with information that lets us calculate exactly where the satellites are in space. By comparing timestamps from

ATOMIC CLOCKS

To be able to provide navigation to the nearest few metres, extremely precise and stable clocks are needed onboard GNSS satellites: atomic clocks. With counters based on the frequency of oscillating atoms, they can keep time to within three billionths of a second.

different satellites at different locations, we can work out exactly where (and when) we are, as GNSS receivers don't just calculate position to within a few metres in good conditions, but also calculate time to within a few nanoseconds too.

MINIMISING ERROR

In the late 1990s, civilian GPS signals were intentionally degraded by an inbuilt feature called 'selective availability'. This was designed to prevent the US's enemies from using GPS to their advantage and introduced errors of 50 metres horizontally and 100 metres vertically. It was disabled in 2000 for various reasons – primarily because academics and commercial enterprises across the world had developed a variety of methods to counter it.

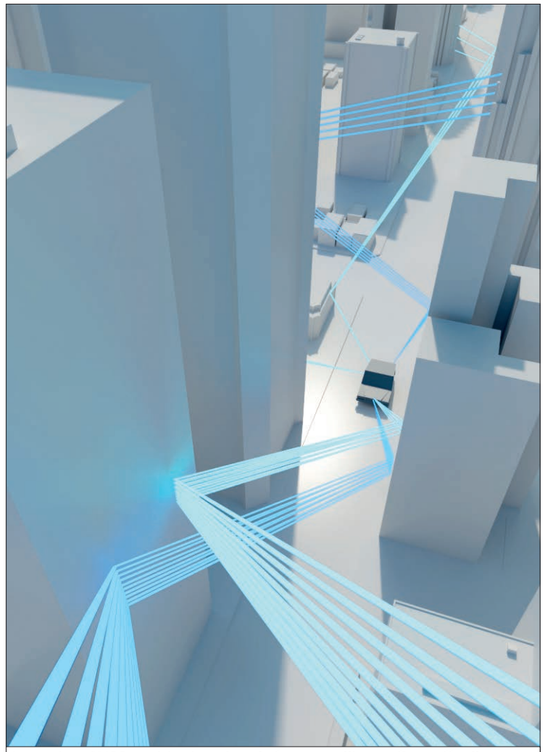
With the flick of a switch, civilian GPS accuracy went from 50 metres to 5 metres and the world changed in a way that many people have never considered. Imagine if your sat nav was always wrong by at least 50 metres? How annoying would that be for door-delivery services like Deliveroo and Amazon? How dangerous would it be for the emergency services? Precise GPS-based technologies that we take for granted today, such as those in autonomous agriculture systems and low-cost drones, could not have been developed. Our fitness trackers would be useless. However, even with selective availability disabled, there are still places where we encounter high GNSS errors to this day, such as in cities.

Today's consumer watches and smartphones determine location using more than just GNSS data. They incorporate Wi-Fi and cellular positioning, as well as using inertial data from accelerometers and gyroscopes, which measure directional change and orientation as you walk, run or drive. They can also include a digital compass that senses the Earth's magnetic field. Finally, a tiny barometer helps to calculate an accurate height measurement. All this data can be combined to provide the most accurate position fix available, and to help to maintain position estimates in regions where GNSS signals are blocked, such as indoors. But can we also change how GNSS works to improve performance right at the very core?

MAXIMISING ACCURACY IN CITIES

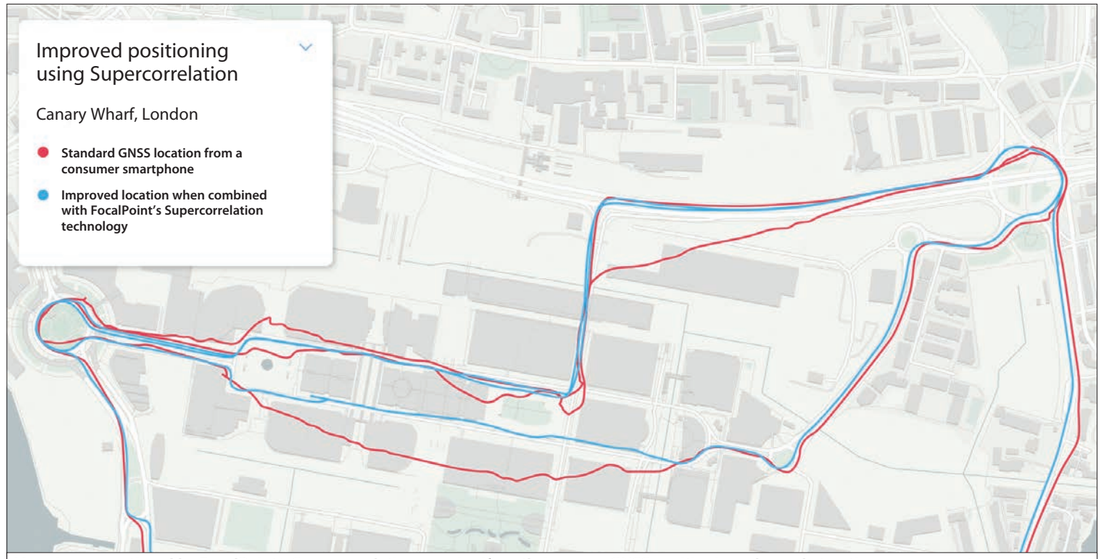
GNSS receivers struggle to maintain high accuracy in cities because the signals from the satellites can be blocked by buildings and bounce around between them, leading to incorrect measurements being processed by the GNSS chip. It is likely that most people have experienced confusing or incorrect GNSS fixes while trying to navigate in a built-up area.

Canary Wharf, London's financial district, is an excellent example of a difficult GNSS environment: a forest of skyscrapers with highly reflective surfaces. It's what is sometimes called an 'urban canyon', as there is limited view of the open sky and, as a result, the satellites. This means any GNSS device in the vicinity will be inundated with reflected copies of the signal as they bounce around between the buildings. A normal receiver will detect all available versions of the signals and be unable to tell the difference between a signal that has arrived on the line-of-sight path, and one with extra delay from reflections. The result is poor positioning, such that your location may appear across the street or further away from where you actually are. Although that might cause havoc with getting to your destination or finding a driver from a ride-hailing app, it could present real safety challenges if autonomous vehicles are to rely heavily on GNSS.



Incoming GNSS positioning signals from satellites reflect off tall buildings in urban canyon environments like Canary Wharf
© Focal Point Positioning

However, a solution to these urban GNSS challenges may be just around the corner. One approach comes from Cambridge-based startup FocalPoint. The company has developed a software-based GNSS technology called Supercorrelation, which performs position calculations using only the measurements from line-of-sight signals. It does this by determining the arrival angle of signals, allowing it to keep any signals that have travelled in the correct straight-line path from the satellite, while discarding reflected signals that arrive at the user from other directions. According to the company, the result is consistently accurate and reliable fixes, even in the most difficult signal environments.



Mapping corrections like FocalPoint's Supercorrelation can significantly improve GNSS positioning where obstructions are present
© Focal Point Positioning

Supercorrelation's approach combines sensor fusion, machine learning and signal processing, developed over several years by FocalPoint's expert team. But FocalPoint isn't alone in developing a solution to the urban canyon GPS issue. The company has developed another approach in collaboration with Google. This is currently used in Android devices and provides mapping corrections based on Google's own 3D models of buildings in nearly 4,000 cities around the world.

KEEPING ATHLETES TO TIME

The COVID-19 lockdown saw GNSS being stretched to its limits in the world of elite sports, as marathons and official championship-status events were staged virtually. These required runners to upload their sports watch data to determine medal places. In one case, there was a gap of just 0.05 seconds between second and third podium places. It is unlikely that the current consumer-grade GNSS chips in sports watches are accurate enough for that decision to have been any more confident than the flip of a coin.

This is another challenge FocalPoint has been working towards addressing. The company has developed D-Tail, a human-motion-modelling software package that converts motion patterns in the accelerometer and gyroscope data from a smartphone or sports watch into a 3D reconstruction of motion through space. FocalPoint says it allows accurate positioning to be maintained as people move in and out of buildings, and provides the most accurate metrics for sport-fitness applications, where the combination of information from GNSS and human-motion-modelling software provides more precise metrics than either alone can.

ENABLING AUTONOMY AND INDOOR NAVIGATION

While it's important to provide high-performance wearable technology to athletes so they can use accurate data to govern their training, shape performance and shave precious seconds off race times, precision positioning will have a far greater impact elsewhere. Centimetre-level accuracy is already being used in China for early-warning systems for landslides with the BeiDou GNSS network. Expanded elsewhere, it could make possible further applications in disaster planning and recovery.

Looking to more commonplace applications, technologies such as FocalPoint's will enable autonomous vehicles and drones to navigate more safely in cities, mountainous areas and forests. We may see last-mile delivery robots navigating pavements, or apps that help us navigate to the right train platform or supermarket shelf. And of course, we will never again get lost in Canary Wharf.

BIOGRAPHY

Dr Ramsey Faragher is President, Founder and CTO of FocalPoint. He is a world-leading expert in positioning, sensor fusion and machine-learning for navigation systems. Alongside his roles in FocalPoint, he is a Fellow of the Royal Institute of Navigation and a Bye-Fellow of Queens' College at the University of Cambridge.

QUICKER TESTING FOR COVID

DnaNudge's consumer genetics technology has been adapted to deliver an award-winning rapid, lab-free test for COVID-19
© Pixabay/Mahmoud-Ahmed

Testing for COVID-19 has become routine for almost everyone, from schoolteachers and shop workers to actors and dancers. An award-winning test that doesn't require specialist laboratories or trained clinicians to analyse the results is being used in UK hospitals and has helped organisations such as the Royal Ballet and the London Symphony Orchestra to ensure that their shows can go on safely. Stuart Nathan spoke to Professor Christofer Toumazou FREng FRS FMedSci of Imperial College London about his rapid, affordable COVID-19 test, based on lab-in-a-cartridge technology, that provides results in just over an hour.

Did you know?

- An interdisciplinary team has created a simple swab test that analyses individuals' genetic profiles
- The test maps people's unique DNA and nudges them towards healthier food shopping choices
- It has now been adapted to accurately detect the SARS-CoV-2 virus from saliva samples on-site in just over an hour

If it hadn't been for a family health crisis, Professor Christofer Toumazou's career may not have gone in the direction that has now won his team the Royal Academy of Engineering's MacRobert Award – the longest-running award for engineering innovation in the UK. In 2021, DnaNudge, created by biomedical Professor Toumazou and geneticist Dr Maria Karvela – CEO and CSO respectively of the London-based startup – won the award for its pioneering genetic testing technology, which has pivoted and was adapted into a rapid, lab-free RT-PCR test for COVID-19 in NHS hospitals.

Having working in electronics for telecommunications, Professor Toumazou embarked on this new path because both he and his wife had inherited a single copy of the same faulty gene, which in 2007 caused their son, Marcus, to develop severe kidney disease. After Marcus suffered organ failure, the Toumazou family spent a great deal of time in London's Great Ormond Street Hospital for Sick Children, where Professor Toumazou realised that healthcare related to genetic conditions focused too much on treating the effects of disease rather than preventing its worst effects from developing.

"Had we known that Marcus had inherited this condition there were things that we and the health system could have done earlier," Professor Toumazou explains. "That could have avoided the side-effects he experienced because we didn't know early enough. I witnessed first-hand how primitive chronic disease management was in a home setting. Hospitals often find it difficult to bring in preventative technologies because it means additional cost to the healthcare system. Although it would be cheaper in the long run and better for patients, it is set up to treat disease rather than to prevent it."

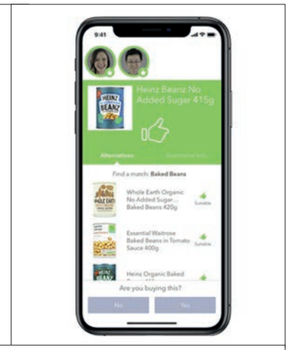
LAB-ON-A-CHIP

Professor Toumazou started thinking about whether his skills in miniaturising complex technology could help develop equipment to carry out genetic testing to detect genes that could potentially have a serious effect on people's future health. "We had invested billions of dollars into consumer-friendly technologies in the telecoms area, but we've invested very little into consumer health and in using technologies in a way that can help consumers look after their own health."

The lab-on-a-chip concept was then in its infancy, but Professor Toumazou realised that it could have potential for this kind of application; with his knowledge of design and fabrication of silicon wafers he could be well placed to develop it. While his background was in electronics and semiconductors, he had little knowledge of microfluidics – the branch of fluid dynamics concerned with liquid flow through very small channels – and hardly any knowledge of genetics. Fortunately, only a few years earlier the Human Genome Project, the international research effort to determine the DNA sequence of the entire human genome, had issued its first report, so characterising human genes and finding practical uses for the information was of great interest.

The idea required interdisciplinary working for development. Sir Richard Sykes FRS FMedSci HonFREng, former Chair and Chief Executive of GlaxoSmithKline, had recently been appointed rector of Imperial College London and was keen on interdisciplinary research, which was more commonplace in the pharmaceutical industry and had proved extremely fruitful. "With his backing, I created an Institute of Biomedical Engineering where medics, engineers, biochemists, electrical engineers, and physicists all worked together," says Professor Toumazou. "That interdisciplinarity and collaboration allowed us to develop the complete lab-on-a-chip technology."

The lab-on-a-chip developed from a need to decide whether to attack the problem by sequencing or by detection. Sequencing required analysing large stretches of the patient's genome, a lengthy process needing a lot of processing power. "Sequencing is a very good medical technology that we now value so much today, for example in discovering the SARS-CoV-2 virus's genes, but my heart was more in detection than sequencing," Professor Toumazou says. "I thought that if we could



Once the NudgeBox has mapped the user's genetic profile to key nutrition-related health traits, they can use the wrist-worn DnaBand or the mobile app to scan food products sold in UK supermarkets to find out whether the nutritional contents are a good match for their individual biology

detect genes with mutations that made people vulnerable to avoidable health conditions, we would have a powerful tool."

FISHING FOR SNPS

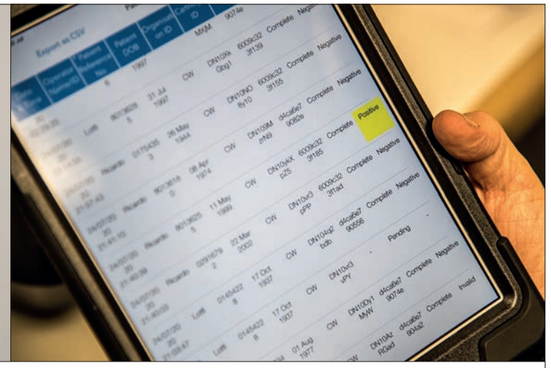
This detection approach led DnaNudge's newly established team to develop a chip similar to devices used to identify active ingredients to target specific receptors on cells. The chip contains a micro-array of 72 tiny wells, each containing a chemical reagent that binds to a genetic sequence of interest. The sequences are known as single-nucleotide polymorphisms (SNPs), conveniently pronounced 'snips'.

"Think of the SNP reagents as being like fishing bait that only catch one species of fish," Professor Toumazou explains. "We decided that the first health conditions we would target were obesity, hypertension and type 2 diabetes, which are huge public health issues putting a strain on the NHS. The genetic mutations – the SNPs – that leave people vulnerable to them are well known, so we baited some of the wells with reagents to detect those SNPs. Although you can collect saliva samples easily, you then have to extract the DNA and make sure there is enough for the reagents to detect the SNP you are looking for."

The chip plugs into a palm-sized circular cartridge, which is then inserted into a 'NudgeBox' – an appliance a little smaller than a shoebox that contains sensors and heating elements. Lab technicians normally extract DNA by pipetting samples into a machine that uses chemical steps to purify the genetic material. Over two to three years, DnaNudge worked with Cambridge-based The Technology Partnership (TTP) to develop a system where every step required for extraction and purification takes place inside the cartridge. "That's the key to decentralisation," Professor Toumazou adds, "allowing unskilled workers to run this with no need for chemistry degrees or understanding of medical devices."

The cartridge has a micro motor in its base – powered by the NudgeBox – that operates miniaturised equipment to extract a sample from a swab and then extracts DNA from the sample, which is minute. Professor Toumazou explains: "Think of DNA molecules as very small 'fish' and as before, the SNP reagents as 'bait', spotted in each well. Each 'bait' will bind to its specific target 'fish'. However, to detect this 'fish–bait' interaction, we need a large number of fish hooked on their unique baits. We use the polymerase chain reaction (PCR) to do that. When DNA is heated, the two strands separate. You can then add some short, single strands of synthetic DNA, which bind to the target strand when it cools. Then, the polymerase attaches to the 'fish–bait' construct and adds on other individual building blocks of DNA (called free nucleotides) to make a whole new double strand. If you repeat this heating–cooling–addition cycle many times you get more copies of the target DNA. The NudgeBox contains all the heating and cooling hardware needed to do this. In less than an hour it extracts the DNA and performs enough PCR cycles to detect the presence of the target sequences. When the target DNA sequences are present in the sample, fluorescence is released proportionate to the number of copies of target DNA. This fluorescence is then detected by the NudgeBox, and a profile in the array of wells is created. The first thing it does is encrypt it so we can throw away the cartridge; we don't keep DNA information."

DnaNudge used the national guidelines for nutrition published by the Chief Medical Officer's office and ensured that these were integrated into the app. The software, hosted on a mobile phone, allows consumers to check their SNP profile against foods' nutritional information using a small wireless barcode scanner to get an instant read out showing whether a particular item is good or bad for them. For example, people with a predisposition to type 2 diabetes must reduce saturated fat and sugar in their diets, while those with a predisposition to hypertension must reduce salt. "It won't say 'you should eat a banana instead of a biscuit', because we know that kind of advice doesn't work," says Professor Toumazou. "What it does say is that these biscuits would be better for you than those others. That's what we mean by the 'nudge'." Professor Toumazou is himself predisposed to hypertension, and by using the system discovered that dry-roasted peanuts are worse for him than standard salted peanuts because of higher salt content in the flavoured coating.



Alongside its use in NHS hospitals, the test is being in used in care homes across the UK. The test also has multiplex capabilities and can check for FluA, FluB and respiratory syncytial virus in addition to COVID-19 © thisisjude.uk 2020

ADAPTING TO COVID

The technology was launched commercially in November 2019. DnaNudge partnered with Waitrose to attract customers and opened a shop in London's Covent Garden to provide the service, adding a series of tests to determine which active ingredients in skincare products were most likely to benefit the customer. "To launch the service, we needed show people that with just small changes they could see definite results. Healthcare and appearance are both appealing things for people to latch onto: in a way, we were appealing to people's vanity to get this off the ground," adds Professor Toumazou.

In January 2020, DnaNudge took its technology to the Consumer Electronics Show in Las Vegas, where it attracted interest from US health retailers. However, cases of COVID-19 were already rising dramatically in China, and just weeks after the team's return from the US, the UK also locked down. The government started to ask industry for ways to help tackle the pandemic. With the genetic sequence of the SARS-Cov-2 virus quickly determined, Professor Toumazou instantly realised that DnaNudge's technology could be useful: instead of detecting SNPs in human DNA, it could detect the virus. "I had deliberately tried to avoid the 'real' medical area, but this threw me straight into it," he explains. "I had discussions with the Department of Health and Social Care, and we agreed we would do this at cost".

Without a laboratory or any manual steps involved, the 'lab-in-cartridge' technology can return results in just over an hour. This rapidity has proved popular in the arts and culture sector, with institutions including London Symphony Orchestra, Glyndebourne Festival and the Royal Opera House – home of the Royal Ballet – all using the tests to support safe rehearsals and performances

The first issue was that the virus contains RNA (ribonucleic acid) rather than DNA, and only DNA can be amplified by PCR. The DnaNudge team developed a technique using reverse transcription PCR to convert RNA to DNA, using a combination of freeze-dried reagents. However, this wasn't very stable and sometimes didn't work, so the team needed to find a way to heat the RNA as well – in less than a month.

Having 72 wells available on the analysis chip allows DnaNudge to include all the viral variants of interest as soon as their genetic sequence is available and allows for a primed well to detect human DNA in the saliva sample from a patient. When a swab is taken, it often doesn't pick up any genetic material at all, which means it can show as a false negative on a COVID-19 test. "Our system includes a control, to check that there is human DNA in the sample – and therefore the swab has been effective – so if COVID-19 isn't detected, you know it's a true negative," says Professor Toumazou. "This tackled a huge problem, as 20% of tests in hospitals were returning false negatives. We did a huge validation in London and Oxford hospitals to satisfy the MHRA [Medicines and Healthcare products Regulatory Agency] and then published a paper in *The Lancet* showing 96% to 97% sensitivity and 100% specificity, meaning we didn't miss any positives."

As well as winning the MacRobert Award in 2021, the Royal Academy of Engineering also awarded Professor Toumazou with a President's Special Award for Pandemic Service in 2020 © thisisjude.uk 2020

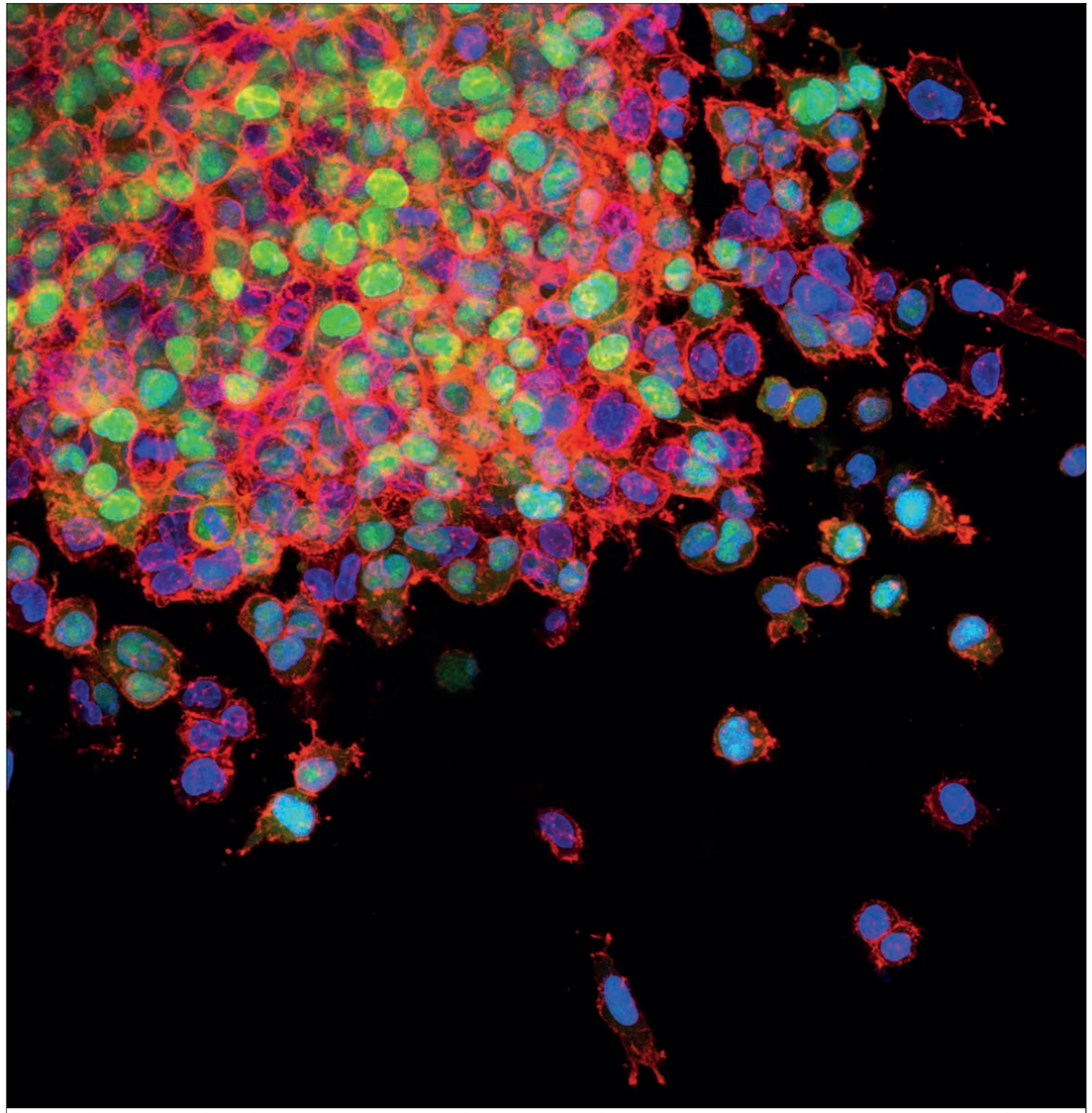
The major engineering problem for the project revolved around the manufacturability of the cartridge. Switching from consumer testing to COVID-19 testing required a large scale-up of production. DnaNudge partnered with a contract manufacturing company Jabil, which makes Hewlett-Packard printer cartridges in Ireland, to manufacture the cartridges. Inkjet printer cartridges have some mechanical similarities with the test cartridges – both depend on precise handling of small amounts of liquid and must be plugged into another box to interface with separate mechanisms. "They helped us understand what they needed, and we helped them with material choice, which machines to use, what quality control was necessary," says Professor Toumazou. "It was a challenging process that otherwise could have taken years."

Although challenging, Professor Toumazou believes that the engineering effort that went into adapting his system to detect COVID-19 may have been a blessing in disguise for future diagnostic applications. He thinks that the technology's most valuable use will be in helping doctors to determine which medicines are likely to be the most effective for patients, enabling them to prescribe and dose based on patients' metabolism of particular drugs and addressing antibiotic resistance. "Lots of bacteria have resistant genes that must be treated with the right antibiotics," adds Professor Toumazou. "The current tests take far too long; while doctors are waiting for results their patients will be on ineffective drugs. This is known as personalised or precision medicine, and there is resistance from pharmaceutical companies as it might impact sales of some of their blockbuster antibiotic drugs. But I hope things are changing. I'm going back to the concept of one chip, one drug."

BIOGRAPHY

Professor Christofer Toumazou FREng FRS FMedSci is DnaNudge's CEO, and Regius Professor of Engineering, Chair in Biomedical Circuit Design, Director of the Centre for Bio-Inspired Technology, and Founder and Chief Scientist for the Institute of Biomedical Engineering at Imperial College London. He is also Co-Founder and Executive Chair of DNA Electronics. In 1994, Professor Toumazou was the youngest Professor ever to be appointed at Imperial College London, at the age of 33.

LIFE ON A CHIP



To study diseases and their possible treatments, cells are typically grown in a dish (like lung cancer cells, shown here as they spread). But could organ-on-a-chip technology offer a route towards environments that more realistically mimic the body, leading to better understand of disease and more effective drug development? © National Cancer Institute / Unsplash

Did you know?

- Organ-on-a-chip technology is used by pharmaceutical companies to test drugs and could reduce the need for animal testing
- To make miniaturised organ models with cell-sized features, bioengineers adapted an electronics manufacturing technique called photolithography
- Organs-on-chips are being used in space to investigate microgravity's effect on the brain, and model a blinking eye and breathing lung

Looking to improve the expensive and slow drug development process and reduce the need for animal testing in the pharmaceutical industry, organ-on-a-chip researchers across the globe are drawing from expertise in engineering, electronics manufacturing techniques, physics, biology, and chemistry to create cell culture environments that more closely mimic the body. Dr Paul Holloway from the Organ-on-a-Chip Technologies Network outlines this new and rapidly developing field.

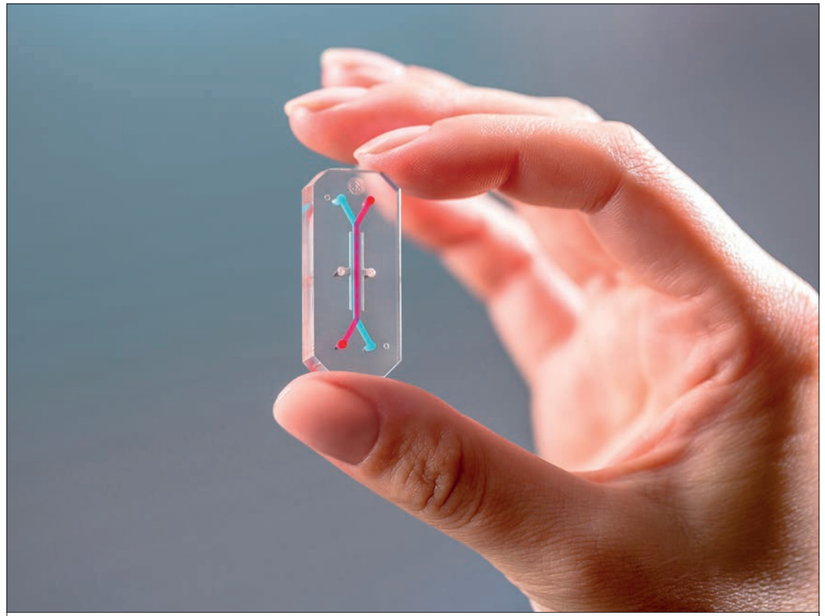
Drug development is painstakingly slow and plagued by failure: 90% of drugs that enter clinical trials in patients don't make it to the market. To get to this point, the established pharmaceutical testbeds acting as analogies for the body are at best lab animals like mice, differentiated from humans by 60 to 80 million years of evolution; or at worst, featureless plastic plates, where cells are grown in a static solution of nutrients. These are a poor substitute for the 78 organs and over 30 trillion cells of numerous different kinds (not including bacteria). That's to say nothing of the ethical implications of testing on animals; the serious side effects patients taking part may experience; or the fact that estimates for the typical cost of bringing a new drug to market range from hundreds of millions of dollars to over a billion.

Enter the organ-on-a-chip. In this emerging field, manufacturing techniques originally designed to pattern circuits and direct electrons in computer chips are being used to create cell culture systems with micrometre-scale architecture to guide cell growth and provide an environment that more closely mimics the body. These new devices aim to improve the drug discovery process and its safety for patients, and to reduce the use of animals in research.

OF CELLS, MICE AND MEN

Cells grown in a dish allow rapid, large-scale testing in a simplified system, well-suited for the 'fail fast, fail often' approach: find out what doesn't work and move on to the next drug quickly before costs escalate. Pharmaceutical companies can test thousands to millions of drug candidates on cells this way. But cells grown in traditional cell culture often fail to reflect the conditions found in the human body. "Many biological experiments are conducted on cells that are inbred, diabetic couch potatoes who sit on a stiff plastic couch without exercise, gorge themselves on sugar once a day, live in their own excrement, and talk only to cells of like mind," says organ-on-a-chip specialist Professor John Wikswo, the Founding Director of the Vanderbilt Institute for Integrative Biosystems Research and Education. The implications of this discrepancy could mean failing a drug that could have worked, or failing to fail a drug and missing what could be a serious side effect.

After the initial drug screening, compounds are tested in animals. Studying how drugs react in the complex environment of a living body can provide crucial information to assess a drug's efficacy and potential toxicity. However, this information comes at the expense of animals, with over a million experimental procedures performed on animals in 2020 in the UK alone. But even putting ethical issues aside, there are still fundamental differences between animals and humans that make animals flawed models for drug testing. While there are a surprising number of similarities across species, not all drug targets are the same. For example, the virus that causes COVID-19 enters a person's cells via a protein on the cell surface called the ACE2-receptor. While mouse cells also have this receptor, small molecular differences mean that the virus doesn't infect mice in the same way. New ways to test drugs in human cells that better resemble tissues and organs are therefore needed.

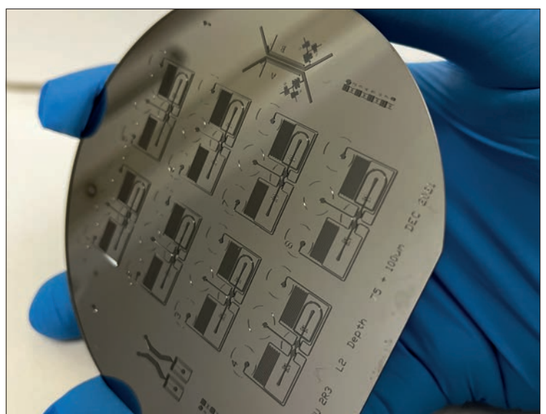


An organ-on-a-chip device designed by Wyss Institute spinout Emulate bIO. Cells can be grown in its microchannels, which are visualised with red and blue dyes © Emulate, Inc

FROM COMPUTER CHIPS TO ORGAN CHIPS

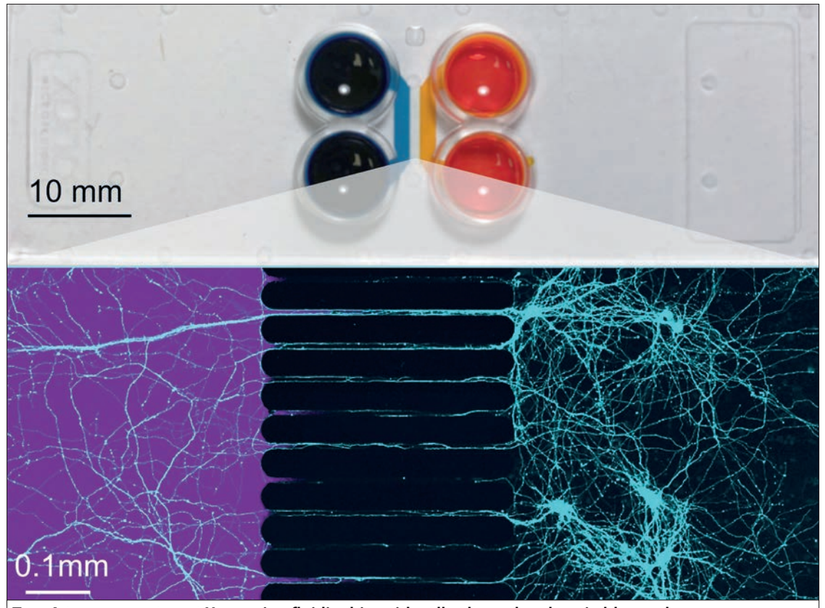
Cells have been shaped by evolution, but also interact with and respond to environmental cues. Some cues are chemical, such as hormones, signalling molecules and nutrients; some are physical, such as extension and compression during movement, or the stiffness of the tissue they grow in. Remove a cell from the body and it quickly changes its behaviour. Without the continuous flow and specific chemical environment of the bloodstream, for instance, blood vessel cells grown in a dish would quickly stop behaving like blood vessel cells. For cells to behave as they do in the body, these mechanical and chemical cues need to be mimicked to create a microenvironment that is more like the original organ or tissue, which helps to structure, guide and shape living cells. All this requires creating cell-scale architecture.

A typical human cell is just 10 micrometres wide – about a tenth of the width of a human hair. To create architecture on this minute scale, bioengineers adapted a technique called photolithography, normally reserved for patterning transistors onto silicon microchips. A raised design made using this technique on a silicon wafer can be used as a mould for a soft, rubbery polymer called polydimethylsiloxane (PDMS), which has the added advantage of being low cost and biocompatible, meaning that it is a good fit for growing cells. Imprinting PDMS with tiny features and sealing it to a glass slide forms channels that can direct fluids and precisely position cells, creating a microfluidic device. By loading this device with the right cell types and chemical cues, bioengineers can begin to create an organ-on-a-chip.



A silicon wafer held to the light reveals the micro-patterns that will be imprinted into a soft polymer to become the channels and cavities that will house human cells

However, microfluidics differs from traditional fluid dynamics. Most engineers working with fluid dynamics must deal with the complex physics of turbulent flow, whether in hydroelectric dams or a jet engine. At the microscale however, the physics is very different. In small channels, the relative importance of viscous (thick, sticky) forces prevails as inertia lessens. This means certain problems are simplified: flows are predictable and can be treated much like an electric circuit, making design relatively straightforward. Meanwhile, other problems require a different approach altogether. For instance, imagine swimming in honey. Getting anywhere is difficult because the fluid



Top: A two compartment Xona microfluidic chip, with cell culture chambers in blue and orange. Bottom: Microscale channels are used to guide connections between axons (coloured in teal) between compartments. The high fluidic resistance of these channels means that a treatment (here a purple dye) can be given to one part of the circuit without directly affecting the other © Xona Microfluidics, Inc

is so viscous, and the inertia of each stroke is not enough to propel you forward. At the microscale, water behaves more like honey. Biology has adapted to this by using different ways of swimming, such as the corkscrew tail of a sperm or a bacterium. Engineers working on microfluidics are now exploiting some of the quirks of physics in microscale channels to control flows of chemicals with high temporal and spatial precision, not only for organs-on-chips, but also for chemical reactions and 'lab-on-chip' applications.

Evidently, all this work requires cross-disciplinary interactions between engineers, biologists, physicists, and chemists. In the UK, the Organ-on-a-Chip Technologies Network is helping researchers do exactly this, providing a UK-based platform to help advance organ-on-a-chip technologies and improve drug discovery. Pharma companies are playing a key role, with GlaxoSmithKline putting TARA Biosystems' beating heart-on-a-chip through its paces and AstraZeneca testing the waters with Emulate Bio's kidney-on-chip. Further afield, Emulate's chips are also being used in high-profile collaborations with Roche and Johnson & Johnson.

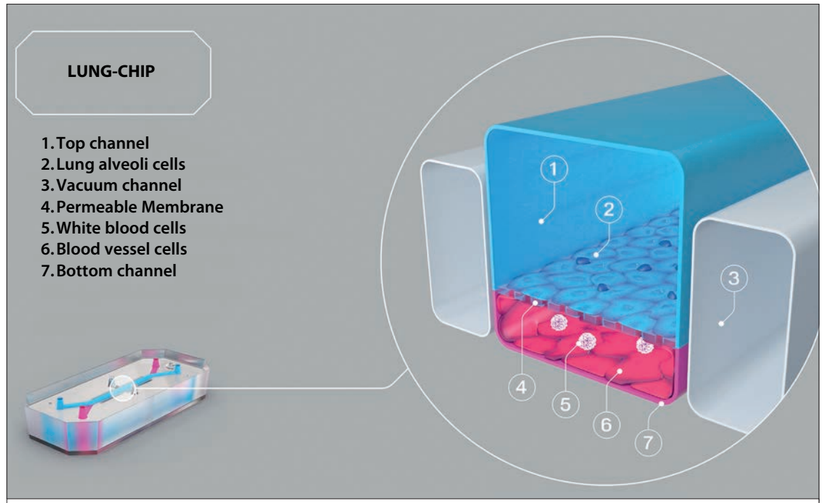
Researchers are also using these different organ-mimicking devices to provide new insights that will help them better understand human disease and discover new potential treatments. From neuronal circuits to study Alzheimer's disease, to a breathing lung-on-a-chip to study COVID-19, researchers are using organs-on-chips to take a closer look at how disease can affect an organ. Fundamental biology is covered too: Emulate is due to send its organ-on-a-chip technology to the International Space Station to study how the brain works under microgravity.

LIVING NEURAL CIRCUITS

A celebrated quote often attributed to Einstein says "everything should be made as simple as possible, but not simpler". Working towards this principle, an organ-on-a-chip does not attempt to completely replicate a whole organ, but instead simplifies it to investigate specific aspects of its function in a context relevant to the question. This could be structural, such as physically guiding neurons' growth. It could be mechanical, such as recreating the flow of blood through a vessel, the breathing motion of the lung or the physical stiffness of the bone. Or it could be chemical and electrical cues, via the signals between different cells.

One example of how microfluidic technologies can distil a very complex organ to a simplified experimental tool is in the brain's neuronal circuits. When neurons are grown in a dish, they do not form the organised circuits we see in the brain on their own. To encourage the creation of simplistic living neuronal circuits, researchers have used organ-on-a-chip devices like the XonaChip® to guide connections between cells in different compartments. Here, filaments called axons protrude from neurons and grow along microchannels smaller than the cells themselves. They link together multiple cell culture compartments to form simplistic neuronal circuits, which can even be integrated with electrical sensors to monitor neuronal function.

Of course, these simplified circuits are a far cry from the complexities of the human brain. While the human brain has about 100 billion neurons, devices like the XonaChip® typically contain around a thousand cells, around a thousand times less than a fly brain. Nevertheless, these systems can be used to simplify complex problems, such as how brain disorders like Alzheimer's disease develop and spread through the brain. Neuronal dysfunction in Alzheimer's is caused by accumulation of a defective form of a protein called tau. Using neuronal-circuits-on-a-chip, research groups at the University of Southampton and the University of Strathclyde have independently been able to track how this defective tau protein can spread through neuronal connections to 'infect' otherwise healthy cells. By enabling new insights into the mechanisms of how this protein spreads between neurons, organ-on-a-chip technologies could help reveal new ways to stop Alzheimer's disease in its tracks.



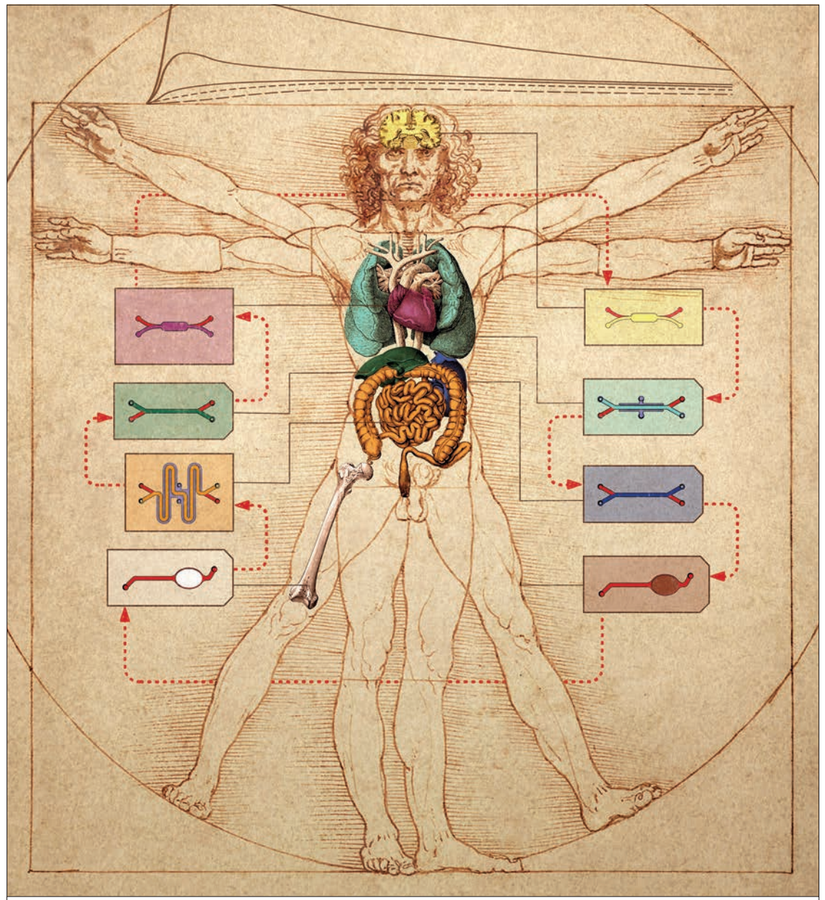
Emulate's lung-on-a-chip allows the lung's mechanical breathing motion to be recreated using vacuum channels © Emulate, Inc

BREATHING LIFE INTO ORGANS-ON-A-CHIP

Organs, of course, do not just consist of one cell type. While patterning single cell types allows new insights into how they function, the real power of organ-on-a-chip technology comes when multiple cell types are cultured together. The first organ-on-a-chip to do this was Emulate's lung-on-a-chip. Zooming in to a cross-section of that device (above), you can see how epithelial cells that usually line the alveoli of the lung were grown on a membrane above a channel coated with blood vessel cells. The upper channel was exposed to air, while in the lower channel, a blood-mimicking media was flowed through. Vacuum channels that flank the central cell culture chambers were then used to stretch the rubbery device and mimic the cyclic mechanical strain caused by breathing. Remarkably, cells responded strongly to this breathing motion. The barrier formed by the epithelial cells became stronger, and cilia (the hairs) on the cells began moving mucus and clearing debris more effectively, modelling how the lungs remove contaminants.

Growing multiple cell types together also allows researchers to study how they interact. Professor Daniel Pennington, an immunologist at Queen Mary, University of London (QMUL), is now using these lung-on-a-chip systems to study how COVID-19 can not only affect lung cells but also cause blood vessel dysfunction. By comparing the effects of plasma from severe COVID-19 patients and healthy controls in the chip, the researchers will be able to study how interactions between blood vessel cells and lung cells can be disrupted. With a few tweaks and by populating it with different cell types, the same device can be used to mimic different organs and diseases. In fact, QMUL has recently established an organ-on-a-chip research centre in partnership with Emulate, using its chip technology to study organs from kidney to colon. Elsewhere, Swiss biotech company AlveoliX, Delft-based BI/OND and Cambridge's CN Bio have been developing their own microengineering approaches to construct other types of organ models, from circulation in blood vessels to oxygen gradients in the liver.

Other researchers are building their own custom chips in-house. At Brunel University, a team of life sciences and engineering experts, led by mechanical engineer Dr Ruth Mackay and toxicologist Dr Elisabete Silva, are developing models exclusively focused on women's health. Four main organ-on-a-chip models replicating the breast, vagina, ovary, and placenta will primarily be used to study cancer and bacterial infections. To allow them to produce custom 3D micro-environments that are optimised for specific cell types, the team is incorporating bioengineering techniques such as electrospinning (using



Linking multiple organ-on-a-chip devices could be used to test drug absorption, distribution, metabolism, excretion, and efficacy in 'body-on-chip' studies © Wyss Institute at Harvard University https://wyss.harvard.edu/technology/human-organs-on-chips

electric charges to spin polymer fibres) and 3D printing, alongside soft lithography.

BODY-ON-A-CHIP

The use of organs-on-chips by pharmaceutical companies like Johnson & Johnson and Pfizer to evaluate candidate drugs is a huge step forward from cells in a Petri dish. But drugs don't just affect one organ, they affect the whole body. A drug meant for the heart might be taken up through the gut, metabolised by the liver, then travel through the bloodstream and ultimately cause a toxic side effect in the kidney.

So, what about linking chips together to make a body-on-a-chip? It certainly poses a huge and complex challenge, but this hasn't stopped researchers pushing the boundaries.

In 2018, CN Bio and the Massachusetts Institute of Technology (MIT) successfully linked 10 organs-on-chips together, each consisting of over a million cells. In 2020, the Wyss Institute reached the same milestone at the end of an eight-year, $37 million project. This work also integrated new mathematical and computational modelling techniques to allow analysis and interpretation of how these readouts scale in relation to our own, complex, life-sized human bodies.

Looking to the future, if new technologies can be developed that allow patient-specific cells to be used in these models, it could mean that eventually, drugs could be tested on a 'mini-me' on-chip before they ever reach a patient.

BIOGRAPHY

Dr Paul Holloway is a researcher based at the University of Oxford developing new organ-on-a-chip models to study stroke and neurological diseases. He is a member of the UK Organ-on-a-Chip Technologies Network, whose aim is to promote organ-on-a-chip technologies and develop a vibrant multidisciplinary research community.

AVERTING HIDDEN CORROSION

Pipelines are at the mercy of the elements, which fast-track corrosion. If allowed to gain a foothold, corrosion can cause chemical spills that devastate their surroundings © Leonid Ikan/iStockphoto

The oil and natural gas that provide over 55% of the world's energy are transported by enough pipeline to circle the Earth 30 times. Corrosion is a huge problem for all this infrastructure. Catastrophic leaks can be caused by centimetre-sized holes, while some types of corrosion are hidden from view altogether, until it's too late. Geoff Watts talks to sensing expert Prafull Sharma about a new detection tool he developed with his team at Cambridge-based startup CorrosionRADAR to combat one of the most insidious types of corrosion.

Did you know?

- In recent years, millions of litres of oil have leaked from corroded pipelines, devastating ecosystems on land and at sea
- Corrosion can be caused by microorganisms living in oil sludge
- Along with a variety of higher-tech solutions, sniffer dogs can also detect hidden corrosion

In 2006, a pinprick-sized hole, which gradually expanded to a diameter of less than two centimetres, was responsible for one of the worst oil spills to hit the tundra of Alaska's North Slope. After 267,000 gallons of crude oil leaked from the corroded pipe at the Prudhoe Bay facility, oozing beneath the snow, government officials said it could take up to a decade for the tundra vegetation to return to normal. Experts believed the cause was corrosive bacteria, growing inside the pipe.

Two and a half years later, at the same facility, a high-pressure natural gas pipeline ruptured, launching pieces of mangled steel across the tundra. Luckily, neither loss of life nor environmental catastrophe took place as a result. Like the 2006 spill, the rupture was caused by corrosion, but this time, the culprit was not bacteria. Instead, moisture accumulating inside the layers of insulation and weatherproofing cladding around the pipe had caused the rupture – a phenomenon known as corrosion under insulation.

Corrosion, you might say, is to engineers what cancer is to doctors. Not literally, of course, but they do share a clutch of similar characteristics. Both can be triggered by the conditions in their surroundings. Both may be far advanced before detection. Both can sometimes be spotted by eye, but not always. If allowed to proceed unchecked, both can be destructive. The cost of remedying them when spotted late in their development is often high.

Corrosion and cancer also share one other feature: the benefit of early detection. Just as doctors have paid increasing attention to this, so have engineers – with good reason. The cost of corrosion to health and safety, to the environment, and to industry in monitoring and remedying it, is staggeringly large. Indeed, the economic cost of corrosion is staggering – estimated at more than £2 trillion annually worldwide, or 3% to 4% of global GDP (gross domestic product). Unsurprisingly, researchers are developing new measures to detect corrosion before its destructive consequences can take place.

CORROSION: THE BIGGER PICTURE

Corrosion typically describes the degradation of metals, caused by chemical or electrochemical reactions with the surrounding environment. Rust is the most well-known form of corrosion: the oxidation product of ferrous metals, such as iron and steel, when exposed to oxygen and moisture.

However, there are many other causes of corrosion. For example, the corrosion that caused the catastrophic Alaska oil spill in 2006 was microbial. Bacteria had colonised the sludge that collected at the bottom of the pipe and formed a film with corrosive conditions. This is also a huge problem for the aviation industry, as bacteria can eat away at parts of an aircraft's fuel tanks.

In marine environments, on the other hand, galvanic corrosion can cause major problems. This form of corrosion occurs when two different metals or alloys are partially in physical contact and immersed in an electrolyte such as seawater. It has afflicted Navy ships and the Statue of Liberty but can also be observed, somewhat less calamitously, if leftover lasagne is stored in steel cookware under aluminium foil.

INVISIBLE DESTRUCTION

One recently developed early detection technology is now finding a key role in the oil and gas industries. Paradoxically, its primary value is in detecting corrosion at sites where you might imagine it would be most easily spotted: exposed pipe work. Look at any oil refinery or petrochemical plant and one of its striking features will be a jumble of large, exposed tanks and tubes linked by interconnecting pipes that twist around and between them. You would think that corrosion here would surely be visible and easily discovered.

Not so. Although generally accessible, many pipes, pressure vessels and other components are insulated to keep the fluids inside at an optimum temperature. The insulation material is protected from the elements by a metallic casing. But such coverings are seldom wholly effective and some moisture, mostly rainwater, will find its way in. Any accumulation of moisture between the insulation and the surface of the innermost iron or steel pipes promotes corrosion, in the form of rust, that may become visible only when the insulating material is removed. The phenomenon, corrosion under insulation, accounts for some 60% of pipeline failures in the oil and gas industry alone. It can be tackled in several ways – and now mechanical engineer Prafull Sharma and his colleagues have added one more.

Having spent many years working for General Electric, Sharma was aware of the damage caused by corrosion. The model solution he had in mind was the nervous system of the human body. The sensory nerves that carry pain messages to the brain do more than signal the existence of such pain; they also pinpoint its location. What Sharma wanted was a system that would continuously monitor for corrosion in an industrial installation and tell the operator the site of any trouble.

Pipe work at refineries is one of the places badly affected by corrosion under insulation. It can become visible at the bottom surface of pipes, where moisture is most likely to accumulate

During his PhD at Cranfield University, Sharma co-invented a technique to do just this, inspired by time-domain reflectometry, which is used by the telecoms industry to detect flaws in cables. In this technique, an electromagnetic pulse is sent along a suspect cable. If a fault is encountered, the pulse will be partially reflected; if not, it will be reflected back upon reaching the end. Knowing the originating pulse's departure time, the arrival time of any partial reflections, and the velocity of the pulses, the operator can calculate where along the cable the fault is located.

DETECTING MOISTURE, DETECTING RUST

For rust to form, moisture must be present: so in a sense, water is a marker of rust. This means a technique able to signal the presence of one will highlight the likely existence of the other. Even if corrosion has not yet begun, being able to detect the key factor driving it – water – opens the way to preventive intervention.

Sharma's invention, electromagnetic-guided radar, uses the same principle as time-domain reflectometry. It relies on a long, thin, flexible sensor laid along the surface of a pipe or storage vessel, beneath the overlying insulation. Its positioning is chosen to ensure that it runs wherever moisture is most likely to accumulate: on the lower surface of pipes, for example. One end of the sensor wire is connected to a control box that delivers the electromagnetic pulse. The wire acts as a waveguide (a structure used to direct waves along its

Left: Moisture sensors are fitted underneath insulation and metal cladding. Right: A control box that sends data from connected sensors to plant workers © CorrosionRADAR

length). As the pulse travels along the sensor, the presence of moisture anywhere along its length triggers the partial backward reflection of any pulse traversing it.

This partial reflection arrives back at the control box before the original pulse (which will have travelled on to the end of the wire and been reflected). Using the time difference between them allows the system to locate the moisture that triggered the reflection and therefore, the conditions that foster corrosion. If moisture is detected in several places on the sensor, it will generate multiple reflected signals. Data from the system is then transmitted to its operators for analysis, who can plan repairs if needed. It can even be used to predict the conditions that foster corrosion in a pipeline or plant. Armed with this understanding, operators can plan a programme of proactive maintenance to minimise their individual risks.

In new installations the sensor wires can be fitted to pipes and vessels during construction, and before the overlying insulation is applied. To use electromagnetic-guided radar in existing infrastructure, insulation must first be stripped off – a routine maintenance process. The frequency of these replacements varies according to the location of the plant, and other local circumstances. It may be as often as every three or four years, or as infrequently as once a decade.

Now, this predictive corrosion monitoring tool has been patented and commercialised by a Cambridge-based company, CorrosionRADAR Ltd, of which Sharma is Chief Technology Officer and Co-Founder, along with Chief Executive Officer Chiraz Ennaceur and Chief Operating Officer Mehrdad Silatani. The company has already caught the attention of several agencies that advise corporations on the topic, and has worked with several international energy companies. Some 10 plants in locations from Europe to Thailand have installed the system.

Electromagnetic-guided radar provides a way to continuously monitor extensive networks of pipes and vessels and alert workers not only to the existence of corrosion, or the risk of it, but its location

Direct cost comparisons with other corrosion detection techniques are difficult to calculate, as most of them are used for spot checks if corrosion is already suspected. Electromagnetic-guided radar, by contrast, is a continuous monitoring system. Real-world data is still limited as none of the systems implemented have been in place for more than three years yet. But based on experience so far, Sharma talks of 65% overall cost savings in periods where electromagnetic-guided radar is used instead of conventional practices. An incidental benefit is that the technique will also detect leaks caused by corrosion inside a pipe or vessel.

Although CorrosionRADAR's tool is fairly distinctive commercially, the team is not the only one to have come up with using guided electromagnetic waves to detect corrosion. Between 2008 and 2012, researchers at Imperial College London's Research Centre in Non-Destructive Evaluation pointed out that a metal pipe surrounded by a metal jacket of the kind often used to clad the insulating material constitutes a coaxial waveguide (meaning a waveguide made from two concentric metal cylinders). Microwaves, they suggested, could propagate through the insulation between the two metallic surfaces. They devised antennae, placed within the insulation, to generate microwaves. Although the method worked in laboratory trials, it was not taken forward commercially.

As often in non-destructive testing, there is no one technique that fits all circumstances. But many of the established methods are inspection techniques intended to offer a definitive diagnosis in one location at one time. Electromagnetic-guided radar provides a way to continuously monitor extensive networks of pipes and vessels and alert workers not only to the existence of corrosion, or the risk of it, but its location. Other methods can then be used to inspect the area of concern in more detail. All told, perhaps this physiology-inspired technique can, in tandem with a toolkit of others, help to keep the blood vessels of today's energy system safely flowing, leak-free.

TACKLING CORROSION UNDER INSULATION

The simplest approach to detect corrosion under insulation is to remove cladding and insulation to expose the concealed surfaces at risk. Cutting windows through the insulation allows sections of pipe to be inspected. However, as scaffolding is needed to access some pipes and vessels, more extensive removal is time-consuming and prohibitively expensive. Although insulating materials are periodically replaced, at which point the pipework underneath can be viewed, these scheduled operations are not frequent enough to spot all instances of serious corrosion.

Several non-destructive testing approaches have a part to play in detecting corrosion under insulation, although there is no one perfect method to do so.

Ultrasound thickness testers can measure the thickness of a pipe or other structure in a specific location and detect internal as well as external corrosion. But this approach still requires insulation to be removed. Another very different form of ultrasound testing, guided wave, can be used to examine lengths of pipe but is thought to be more helpful in spotting internal defects than external corrosion.

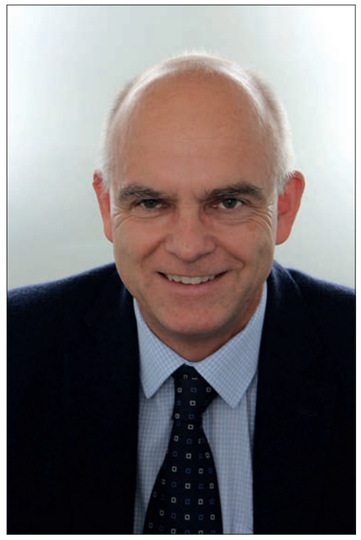
Some types of radiography can be used to assess hidden pipes without removing the insulation. Here, X-rays, gamma rays or neutrons are fired at a material, which they travel through before being captured on a detector.

The same advantage holds for pulse eddy current inspection, which uses a direct current coil to induce a magnetic field in the pipe under inspection. Turning off the power leaves eddy currents in the pipe. The length of time that these take to dissipate is determined in part by the average thickness of the pipe's wall. Sniffer dogs, thermography and neutron backscatter also have their advocates.

BIOGRAPHY

Prafull Sharma is Chief Technology Officer at CorrosionRADAR. He co-invented electromagnetic-guided radar, among several other inventions, and has over 16 years of industrial experience. Previously, Prafull worked for General Electric R&D where he developed several sensing technologies. He has a PhD from Cranfield University and an engineering degree from the Indian Institute of Technology Madras.

AN INNOVATOR WHO FILLS A VACUUM



From outer space to the depths of the earth, Professor Trevor Cross FREng seeks new uses of the technologies that enabled the electronic revolution. Vacuum tubes may no longer be the glowing heart of radios and televisions, but in some applications they reach places that are beyond semiconductors. Along with their associated electronic systems, vacuum devices also play an important part in quantum technology and its promise to revolutionise computing.

For Professor Trevor Cross FREng, Vice President for Innovation, Space and Quantum at Teledyne e2v, a career in engineering began with instructions to turn a research project into a business opportunity. General Electric Co. Ltd's (GEC) Hirst Laboratory in Wembley had done brilliant research on gallium arsenide (GaAs) solar cells and when it came to exploiting that R&D, Professor Cross's brief was to 'take that process and machinery from GEC-Hirst and bring it to the English Electric Valve (EEV) manufacturing site in Chelmsford, a part of GEC'. He then turned the R&D into the ability to make some of the world's highest-efficiency solar panels for small spacecraft.

Professor Cross had spent time at EEV, in 1978 for a pre-university gap year, before he embarked on an engineering career. Chelmsford was the home of EEV, then a part of GEC Marconi, which was one of the UK's leading engineering businesses. He returned to EEV in 1985, with a physics degree and a PhD in radiation damage in compound semiconductors. He is still based at Chelmsford, albeit after six different name changes for the business. Now part of the Teledyne family, the Teledyne e2v site remains the city's last significant manufacturing employer with around 1,000 people. Today, Teledyne e2v specialises in high-tech, low-volume specialist technology, such as space technology and the growing area of quantum technology.

A HISTORY OF TECHNOLOGY

Chelmsford was the original home of Marconi – the company built the first ever radio wireless sets – and that spawned what became EEV to make the vital radio 'valves'; later both became parts of GEC. "Famously," says Cross, "the first batch of radios included one for the Titanic. If it wasn't for that radio set, everybody on board would have drowned." The maritime disaster proved to be Marconi's saviour. "That incident, although it was absolutely terrible, really launched the Marconi Company. It was heading towards going bust until suddenly everybody said 'if we've got a big ship, we should have one of these new-fangled wireless sets'."

Over four decades later, it was a very different kind of historic event that catalysed the launch of the business's vacuum tubes. In 1953, the coronation of HM Queen Elizabeth II created a rush to buy TV cameras to cover the ceremony. The cameras, built around image sensors that were vacuum tubes the size of a person's arm, were the size of a domestic refrigerator and those tubes alone cost an engineer's salary for a year! The coronation also led to a booming demand for tubes for TVs to watch the broadcasts.

To this day, vacuum tubes account for more than half of e2v's profits. Although TVs and cameras no longer need vacuum tubes, microwave ovens often use a vacuum tube device, a magnetron, which produces pulses of microwave energy from pulses of DC electricity. The company also makes a giant version of these devices that power miniaturised linear accelerators generating X-rays for cancer radiotherapy.

EEV still had annual sales of near on £60 million when GEC Marconi closed. There was clearly enough demand for the very mature technology of vacuum tubes, augmented by a family of solid-state technologies and products that had grown from the technical skills needed to make the tubes, to interest investors who might want to back this part of Marconi's business. The demand continues to this day, thanks to an ageing population, rising standards of healthcare, and wider availability of cancer radiotherapy, especially in China and the east.

BUYOUTS AND TAKEOVERS

Professor Cross recalls that, in the bid to rescue EEV, he was brought onto the management buyout team because, as advisers put it, he was "the technical person that the investors would trust". He became Technology Director when 3i funded the £72 million buyout to found e2v in 2002. Two years later, the company floated on the stock exchange.

As technical lead, Professor Cross managed e2v's technology through 12 years as an independent business. The company was one of a relatively small community of specialist technology businesses that knew each other well and were circling around each other in search of mergers and takeovers that might deliver business

QUICK Q&A

What inspired you to become an engineer?
Without doubt it was watching the Apollo missions.

What are you most proud of?
The team we built for quantum technologies at e2v.

Who influenced your engineering career?
My high school physics teacher – Mr Sharratt.

What's the best part of your job?
Seeing young engineers getting excited by the future of technology.

Do you have a favourite tool or gadget?
My Swiss Army pen knife, which made it to Annapurna base camp with me

Which engineering achievement couldn't you do without?
Microwave oven.

What do you think is an overlooked engineering success?
The 1957 Wurlitzer 2100 Jukebox, which was the first machine to play 200 selections, and the camera in the iPhone 5 – HD, colour and about $5.

Who is the engineer you admire the most?
Henry Ford who said: "'Obstacles are those terrible things you see if you take your eye off the goal."

growth. When e2v was looking for takeover candidates, he led the technology 'due diligence'. It acquired about half a dozen companies before, in 2017, e2v itself became acquisition number 52 for US company Teledyne Technologies. He soon found that Teledyne had taken over some of the businesses that he had explored for e2v.

Professor Cross had enjoyed inspecting the factories for e2v but he wanted to do something new. The Teledyne takeover prompted him to tap deeper into the university links he had established as Technical Director and later Chief Technology Officer (CTO). A lot of academic research, especially in physics, leans heavily on the vacuum technology and electronics that underpin e2v. University researchers delight in pushing equipment to its limits, creating demands that pose challenges and opportunities to suppliers such as e2v, prompting advances that would be useful beyond the academic world.

"When you work in niche markets and high technology, you see some really bright people and some really neat things," Professor Cross says. For example, he had been involved in satellite technology since his early days at EEV when it commercialised research on GaAs solar cells for solar panels, and joining Teledyne added more space expertise to e2v's remit. To pick just one example, another part of Teledyne made the infrared sensors for the new James Webb Space Telescope. So Professor Cross had excellent links with a growing network of demanding, leading-edge science customers.

EMERGING TECHNOLOGY

Around the time of the Teledyne takeover, quantum technology (QT) was starting to move beyond the world of academic research, with policymakers beginning to take notice. Governments saw this as an ideal area of research for targeted support, which led to funding for QT across the world. The UK launched the National Quantum Technologies Programme (NQTP) in 2014 with an initial budget of £270 million, which has since risen to more than a billion.

Left: Teledyne e2v's technology is the heart of the 'CASPA-ADM' 12u cubesat (Cold Atom Space Payload – Atmospheric Drag Mission). This will measure tiny variations in atmospheric drag in low Earth orbit, revealing atmospheric density changes useful in climate modelling and orbit decay prediction. It builds on previous miniaturisation and environmental hardening developed in the 6u cubesat CASPA project (right) with partners including the University of Birmingham © image on left courtesy of Clyde Space

Professor Cross's university contacts also started sharing enthusiastic accounts of the developing discipline, talking about building on concepts and techniques that were already mainstream for e2v. So, he visited universities across the UK and the National Physical Laboratory (NPL) to find out more. He realised that, while university labs had done a lot of proof-of-principle work on new QT sensors, for example, it would need engineering to make useable products that e2v could sell to its wider audience of high-tech customers.

The company already had expertise in photonics, imaging and high-vacuum technology along with its own fabrication facilities for specialist electronic chips. It had also established channels to market in defence and space markets, traditionally early adopters of new applications.

For e2v the challenge was to make the combination work commercially. The company began to develop ideas for its own entry into QT. "We made a play for cold-atom sensors because we have capabilities in vacuum technology," Professor Cross explains. Cold atoms are key ingredients in many QT applications. Since then, the company has expanded its work on QT. Professor Cross established a quantum programme of more than 30 people and has an office at the QT Hub at the University of Birmingham – the first of the four national QT hubs – which he helped to shape.

When research funding started to flow into QT, Cross had already become something of an industry enthusiast and leader in the area. When the NQTP was established in 2014, he joined its Strategic Advisory Board. In 2019, e2v hosted the first meeting of the UK's Quantum Technology Leadership Group. Professor Cross describes this group, which he co-chaired with Professor Graeme Malcolm OBE FREng FRSE of M Squared Lasers, another key player in the QT business, as a 'pre-trade association'. This was the forerunner to the recently established UKQuantum, an industry-led consortium set up to be the voice of the UK quantum industry.

There may not be a large market for QT devices yet, but the beginnings are there. If nothing else, e2v and other businesses are already building the all-important supply chain to deliver the tools that QT will need. For example, e2v has supplied components for the growing quantum computing business. "We make some of the fastest data converter chips in the world and they're needed there," Professor Cross explains. "But it's not part of what I normally call my quantum technology programme."

Nearer to the QT mainstream is the development of a quantum gravity sensor at the University of Birmingham [see 'Quantum gravity with added atoms'] and a quantum miniature atomic clock that e2v is developing with NPL. This £15 million initiative brought together 30 partners from industry and academic research.

FROM RESEARCH TO COMMERCIALISATION

Most engineers might consider Professor Cross's 30-year track record of guiding technology from research through to commercial products to be the classical definition of innovation, especially in such high-tech applications as space, defence and security. While he grudgingly accepts the label, Professor Cross sees innovation as a "horrible word" with "too many different understandings of what it is". For him, innovation means taking IP (intellectual property), new ideas and capabilities and turning them into something that adds value as a public good or commercial value.

He insists that there must be a connection between at least part of what academics get up to and the financial benefits of their work. As he said in an interview about earlier threats to science budgets: "I don't think anyone can have a God-given right or automatic assumption that taxpayers will fund blue-skies research at ever-increasing levels."

This view carries over into Professor Cross's take on the government's enthusiasm for R&D to prime economic growth. He likes the idea but warns that academics should not expect to walk away with all the money. Take the aspiration for the UK to spend 2.4% of its GDP on

QUANTUM GRAVITY WITH ADDED ATOMS

For Professor Cross, there is a natural fit between QT and his role as Vice President for Innovation at Teledyne e2v. QT, a rising area of technology, combines the company's expertise in vacuum engineering and electronics, core skills that e2v is using to develop new ways to measure time and gravity, two promising early applications of QT.

Gravimetry involves detailed measurement of local gravity and how it changes in response to underground features such as buried objects and holes. Conventional gravimetry measures gravity's effect on a test mass suspended on a spring. Instead, a QT gravimeter measures the forces on atoms in a vacuum. This is just one application that Professor Cross's QT team at e2v is pursuing with researchers at the national QT Hub at the University of Birmingham.

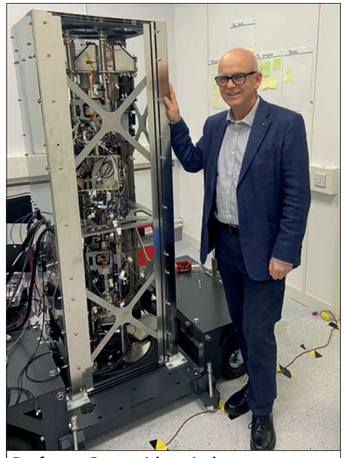
QT gravimetry starts with cold atoms in a vacuum. Professor Cross explains: "We have a little device, a metal tube with a piece of rubidium in it. The tube has a couple of holes or a slit in it. Warm up the tube, pass an electric current through it, and you can put a few million atoms of rubidium into the tube. You can use laser beams like a snooker cue and push these atoms from where you vaporise them into another chamber, where you want to use them."

Quantum gravimetry can be exceptionally sensitive. "If you've got one atom, and you use that as your test mass when you're trying to measure something, it's not that you've got less error, you have no error." But you do need cold atoms. "Atoms have this horrible habit of rattling around if they've got any energy – that's what heat is, the movement of the atoms. Take away that energy and you can stop them from moving around too much. That's what laser cooling does." Essentially, the sensor drops two clouds of cooled atoms over an area, then measures the differences in gravity that occur as the particles are pulled by their surroundings.

Moving the atoms around means that different lasers can measure changes in local gravity. "I can measure the variations in the gravitational strength to something like the 10th and 11th decimal place," says Professor Cross. "I can make inferences about the density changes of the material under my feet. Using mathematics, you can reconstruct an image of what's under the ground. I can find dense objects. I can find holes and I can use that to map the underground."

Spring gravimetry peters out with features deeper than about two metres. "If you could go to five metres and measure something the size of a grapefruit, suddenly you'd access nearly all underground services." That would be a boon for anyone trying to see what's going on underground. The technology could help detect hidden infrastructure, such as pipelines, and prevent needless digging up of roads and pavements. "Companies have said to me: 'if you could find a way to arrive at somebody's kerbside, trundle a little device and it plots out the area to dig where there's nothing in the way, that's worth a lot of money to us.

"I can't do that today. The physics says I should be able to, but the technology is not mature." It is, however, making good progress, with the Birmingham team and its partners at e2v coming up with promising results. Professor Cross was part of a team that used a QT gradiometer outside of laboratory conditions for the first time to locate a tunnel buried one metre below the ground surface, with the results published in *Nature* in February 2022.



Professor Cross with an industry prototype gravity gradiometer based on the university-built prototype

R&D. "Our academic colleagues may be thinking, 'Great, everything's going to rise by, whatever the number is now, up 2.4%. That means loads more money for academic research'." Hold on, he cautions. "You could say, we're not really pulling things through into value-adding commercial activity quite as effectively as we are generating brilliant new ideas. We also need to support the commercialisation part of the process.

"You could generously increase the amount for research in the university base, but disproportionately put more into the innovation process." This would be easier when research budgets are rising. Putting more into applied research and commercialisation wouldn't have to mean taking money out of core research activities. The research share just would not go up as much.

As Professor Cross sees it, the creation and development of new technologies, and using them to create wealth, depends not just on sustaining, but also funding, both bits of the chain. It also needs a healthy innovation culture. He accepts that it will take more than a few successful projects and one company to make a success of QT. As he told the House of Commons Science and Technology Committee when it took evidence on QT: "The industrial players can see ways to solve the technology problems, but unlocking the true value in the economy is not just about the technology. It is about what we encourage people to do with it."

Professor Cross with his Lotus 1973 Elan+2 classic car

CAREER TIMELINE AND DISTINCTIONS

Studied physics with physical electronics, University of Bath, **1982**. PhD in radiation damage in compound semiconductors, Lancaster University, **1987**. Diploma in management studies, Anglia Polytechnic, **1991**. Chair, Electronics, Sensors, Photonics Knowledge Transfer Network, **2009–2014**. Group Chief Technology Officer, Teledyne e2v, **2005–2017**. Fellow, Royal Academy of Engineering, **2020**. Non-Executive Board Member, Compound Semiconductor Applications Catapult, **2017–present day**. Vice President, Innovation, Space and Quantum, Teledyne e2v, **2020–present day**.

THE AFRO HAIR COMB INSPIRED BY PRINTING

Swansea-based engineer Dr Youmna Mouhamad is using her R&D experience to invent a hair comb designed to make looking after textured hair easier and less painful.

During her PhD in polymer physics, Youmna nannied for a young girl named Hazel who had long, thick, afro-textured hair. Like many other children, Hazel would cry from pain and frustration when her mother detangled her hair, even though she took extra care to part it into sections and apply conditioner beforehand. For women, the discomfort of this lengthy process can also be a reason to skip or delay their own hair care later in life, knocking confidence as a result.

This is what inspired Youmna to develop the Nyfasi Deluxe Detangler, a comb specially designed to coat hair with conditioner while detangling, to make the whole process more manageable and pain-free. "My dream is for women and girls to experience the joy of natural hair. I want to redefine hair care, for young girls like Hazel, as an intimate moment when they can connect with their mothers, and for women, as a celebration of themselves," says Youmna.

After her PhD, Youmna became a research engineer at Swansea University, exploring the use of traditional printing techniques with conductive inks to print solar panels and electrical components. Most of the projects she worked on involved commercialising new technologies, which sparked an interest in product commercialisation, business management and marketing. Eventually, she started using her scientific skills and creativity to solve a problem close to her heart: the pain and frustration Black women experience when caring for their hair.

Inspired by flexography printing, a widely used technique to print on paper and thin plastic films (like food packaging), Youmna designed a mechanism for the detangler that enables the application and distribution of conditioner. In flexography printing, a stamp mounted on a rotating cylinder is dipped into an ink reservoir and then brought in contact with the paper, enabling the ink on the stamp to be transferred onto the paper. The mechanism of the detangler is very similar – replacing the ink with conditioner, and the paper with hair.

Left: Dr Youmna Mouhamad with her invention. Right: The Nyfasi Deluxe Detangler

For two years, Youmna worked on the project as a side hustle, building a minimum viable version of the Deluxe Detangler and registering UK and international patents. Then, in 2020, she was awarded an Enterprise Fellowship from the Royal Academy of Engineering, officially marking her transition to entrepreneurship. With the Enterprise Fellowship's support, Youmna was able to refine the detangler's design, improve user experience and develop its packaging. "The Fellowship has been a life-changing opportunity. It empowered me with the time, funds and knowledge to accelerate a good idea into a great product and a viable startup."

Innovation and community are essential values for Youmna and her business. She engaged with 50 women during the product development. "For me, it was necessary to really understand women's challenges and concerns; and to develop the detangler with them, not just for them," says Youmna, who is currently raising funds to launch production of the detangler in the UK as part of her startup, Myana Naturals Ltd.

Youmna also recognises the importance of nurturing the next generation and empowering others. "My biggest challenge was my lack of self-confidence," she says, having struggled with imposter syndrome. Once the detangler is launched, she plans to use 5% of Myana Naturals' profits to unlock the potential of young people and build confident young women through one-to-one coaching, and ultimately sees the Deluxe Detangler as a tool to enable women to love and appreciate their hair.

HOW DOES THAT WORK?

ROBOTIC VACUUM CLEANERS

Twenty years after the Roomba's original release, the latest generation of robotic vacuum cleaners incorporate sophisticated machine vision technology to steer clear of electrical cables, stray socks and pet poo.

Like touchscreens, earphones and 3D printers, robotic vacuum cleaners were once a figment of a sci-fi author's imagination. In a 1950s novel, robotic vacuums were envisaged to circulate homes quietly and autonomously, leaving no area of floor untouched before returning to its charging dock. It wasn't until the late nineties and early noughties that the first few robotic vacuums were released, including the Roomba.

The breakthrough technologies underpinning robotic vacuum cleaners are their ability to independently navigate, along with an array of onboard sensors helping them interpret the world around them. Most newer models use front-facing cameras or LiDAR (light detection and ranging, which uses a pulsed laser to measure ranges), while many older models rely on infrared lasers to identify looming obstacles. By bouncing infrared light from the floor, they can measure the distance to the floor ahead, helping them to avoid impending drops such as stairs. Onboard light sensors can also measure wheel rotation to calculate distance travelled, while bump sensors help them detect collisions before they happen and change direction.

While early robotic vacuums appear to clean almost at random, their movements are actually governed by a set of rules inspired by the behavioural

patterns that describe how simple animals like insects explore the world. These allow them to travel in a straight line, change direction after encountering an obstacle such as a stray toy or piece of furniture, follow along a wall, or move outwards in a spiral pattern. However, this approach can sometimes mean that certain corners tend to get cleaned several times, while other areas may be missed altogether.

Over the years, the navigational ability of robotic vacuums has evolved in tandem with the latest advances in machine intelligence. To make their cleaning more efficient, manufacturers incorporated simultaneous localisation and mapping (SLAM), a computational approach that allows a robotic device (like a self-driving car) to map its surrounding area as it goes. For robotic vacuum cleaners, this translates to tracking where it's cleaned and where it's still yet to clean, as well as marking the location of furniture and optimising future routes. This mapping is also a useful way for owners to prioritise areas that need more frequent cleaning, such as kitchens.

But in 2016, despite their mapping abilities, robotic vacuums started going viral for their inability to dodge pet poo, and the messy consequences. Moreover, they could also still be easily thwarted by rogue shoes, or damage electrical cables in their path. To try to solve these problems, manufacturers such as Samsung and iRobot have incorporated machine vision, building in object detection algorithms trained on thousands of images of common household obstacles, such as socks and electrical cables. Plus, algorithm or not, owners can ensure the tangles of cables underneath computer desks remain safe by setting them as no-go areas.

Mechanically speaking, the underside of a robotic vacuum looks broadly like a conventional upright device, with three wheels for movement and rotating rollers and bristle brushes for cleaning. The latter are usually retracted when not in use, instead emerging as the device is activated to sweep debris into a storage receptacle that typically holds 0.6 litres of waste, about a tenth of the capacity of a classic Henry hoover. Some devices can empty their own bins back at their docking stations, having navigated home once battery life runs low.

These days, robotic vacuums are among a larger digital ecosystem of smart appliances and are often controlled via app, just like Wi-Fi-connected thermostats and washing machines. They can be paired with voice assistants, taking advantage of their inbuilt natural language processing to make scheduling more intuitive. And in case they need to double as something other than a vacuum cleaner, it's even possible to buy models that can mop, serve as a security camera, and communicate with other people in the house.