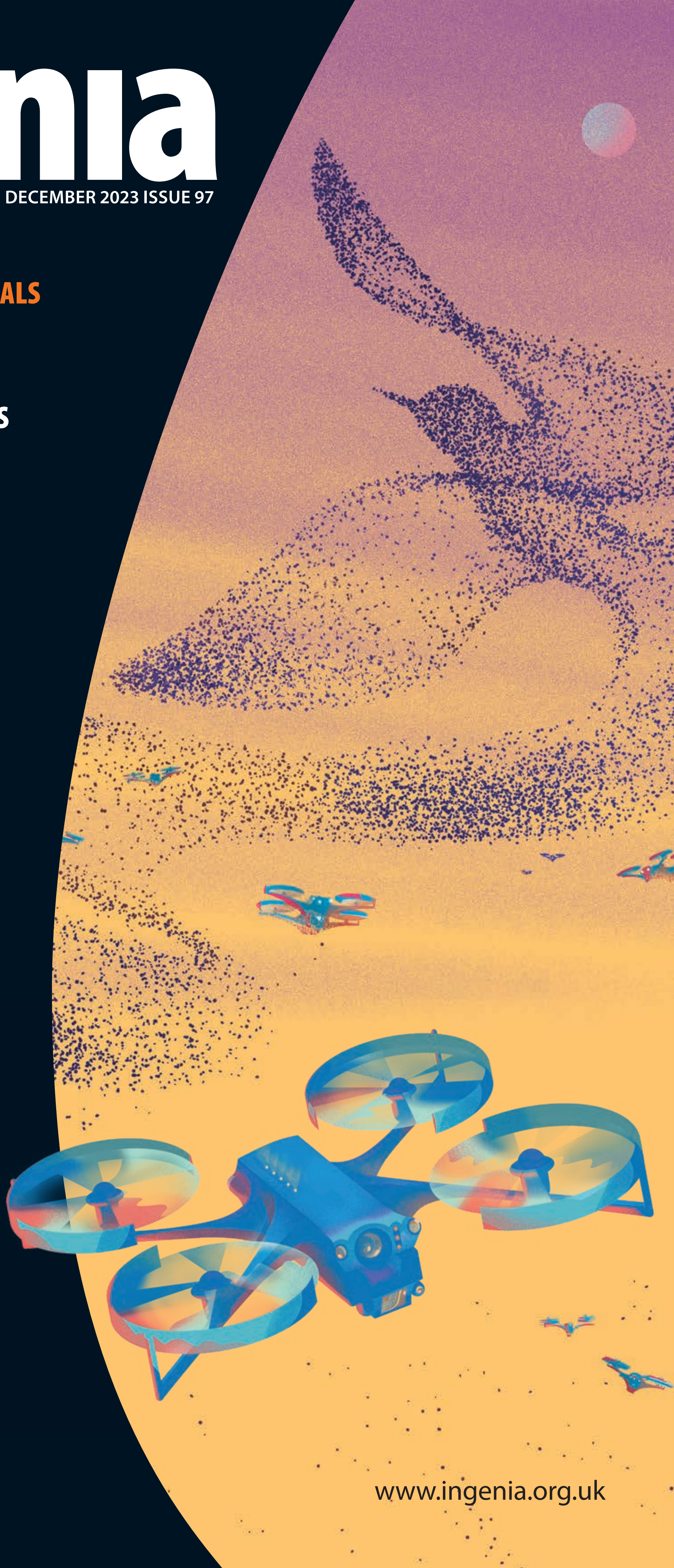
ingenia

DECEMBER 2023 ISSUE 97

REMEDIATING FOREVER CHEMICALS
AUTONOMOUS VEHICLE TESTING
GREENER CARGO SHIPS
ENGINEERING SWARM ROBOTICS



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Front cover
Illustration for *Ingenia* by Benjamin Leon

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WELCOME

Engineering is the key to solving some of the world's biggest challenges, from sustainable solutions to improving people's health.

This can be seen across this issue, particularly in two articles focusing on clean water. On page 16, we look at the ways in which engineers are working to capture and remove forever chemicals – which have been shown to impact human health – from our environment, including water supplies. Meanwhile on page 30, Professor Simon Pollard OBE FREng discusses how his career as an environmental engineer has lent itself to water research and waste management to protect the environment.

With the vast majority of the world's traded goods being transported by sea, shipping is an industry that engineers are working to decarbonise – page 21 looks at the progress so far.

The two winners of this year's Africa Prize for Engineering Innovation have each developed devices that help people and communities. Innovation Watch features FlexiGyn's mobile gynaecology device, which is improving people's access to reproductive healthcare in Africa. Joint winner YUNGA's community 'panic button' will feature in our next issue.

On page 11, read how nature is inspiring engineering and technology solutions – in this case, applied to swarm robotics. And after reading, do visit *Ingenia*'s new website, which has links to films of some of these unbelievable swarms. While you're there, why not dig into *Ingenia*'s vast archive of content, spanning almost 20 years – easily accessible if you're searching by topic or series. Or sign up for our monthly newsletter for access to online-only content.

As always, please let us know what you think of the issue – and the new website – at ingenia@raeng.org.uk or via Twitter using #IngeniaMag.

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

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CONTENTS

IN BRIEF

DRAGONS' DEN INVESTOR MARKS NATIONAL ENGINEERING DAY

Bristol-based Monica Wai (right) and Kira Goode (left), winners of the 'Everyday Engineering' competition

On 1 November, the Royal Academy of Engineering marked National Engineering Day, an annual celebration of the engineering profession. The focus of the day was to show the nation that everyone has the potential to be an engineer, while demonstrating the varied skill sets the profession can require.

This year, the day centred on three major activities: a public 'Everyday Engineering' competition, supported by *Dragons' Den* star Deborah Meaden, that invited anyone and everyone to submit their ideas and innovations for making our lives more sustainable; the release of a special edition 'Engineering Icons' Tube map in partnership with TfL; and an evening event featuring a series of TED-style talks and interactive exhibits.

Throughout October, the 'Everyday Engineering' competition invited the public to release their 'inner engineer' by submitting ideas aiming to make daily life more sustainable. It served as a reminder that engineering habits – such as problem spotting and creative problem-solving – can come from anyone.

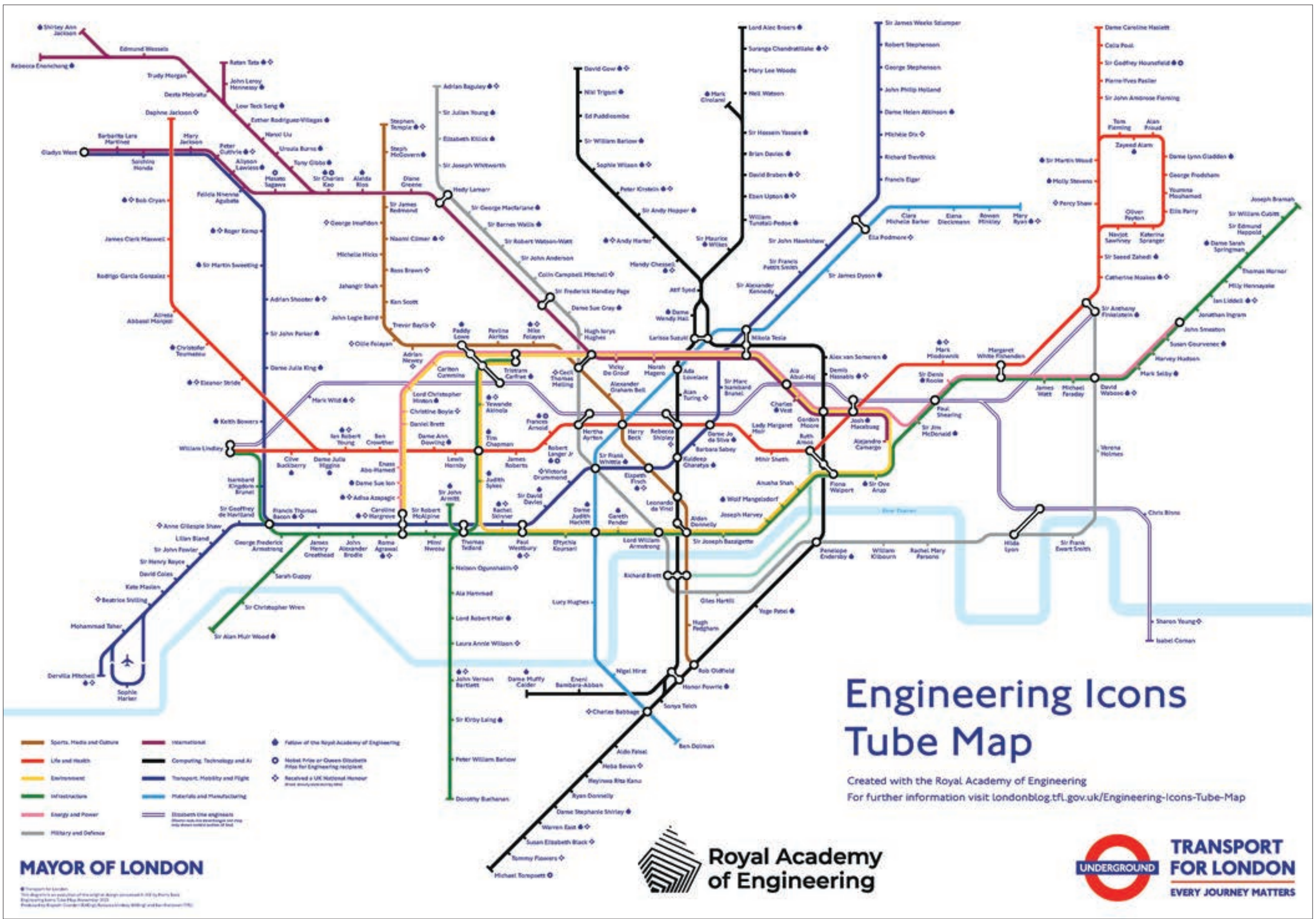
After announcing three finalists on the day, a live social media vote decided the winning entry: Eleria, a portable cleaning and sterilising case for menstrual cups, invented by Bristol-based Kira Goode (24) and Monica Wai (24). Kira and Monica will receive a prize package including business advice from Deborah Meaden, who announced the winner on her social channels on 4 November.

The other two shortlisted innovations were Phyto, a hanging pendant light made from a 3D-printed 'nuisance' algae-based bioplastic invented by Sam Bird Smith (23, London); and coPonics, a customisable vertical farming unit for gardens, invented by Anvith Sujay (16, Bristol) and Ashwin Madhusudhanan (15, Bristol).

The Academy also published public polling data on the day, which showed that 64% of UK adults believe engineers play a vital role in addressing many of our societal challenges, including climate change. Yet, the data also uncovered outdated misperceptions, many held by young people, that could hold back the UK's transition to a sustainable, low-carbon economy, such as:

- 28% of 18 to 34-year-olds believe engineering jobs are better suited to men, compared to just 10% of over-55s
- 39% of 18 to 34-year-olds believe the myth that engineering jobs are mainly based in factories and building sites, compared to just 13% of over-55s.

In the lead up to the day, *This is Engineering* launched season 12 of its campaign videos, featuring robotics trailblazer, Eneni, and net zero navigator, Harvey. The campaign also launched



The 'Engineering Icons' Tube map, which celebrates 274 engineers across 11 themes, including Ada Lovelace, Alexander Graham Bell and Isambard Kingdom Brunel

a new website. This 'one-stop shop' for young people will help to inform them about what it is like to be an engineer and find practical advice on how to become an engineer. Rather than just profiles of young engineers, like its previous incarnation, the new site now features a new section on how to become an engineer, as well as more information about the types of projects engineers work on.

***This is Engineering* protagonist Harvey**

***This is Engineering* protagonist Eneni**

INGENIA GOES DIGITAL

We've launched a new website! So take a look around. Articles are grouped by topic and series, making it easier to navigate and for you to find out more about the things that really interest you.

We'd love to hear your thoughts, so please do let us know at **ingenia@raeng.org.uk**. And if you haven't already, please sign up for our monthly e-newsletter, which points you to our exclusive online-only content, gems from our archive, and the latest engineering events, exhibitions and competitions.

SPORTS AND NUCLEAR PARTNERSHIPS RECOGNISED

The Loughborough University and adidas team with their award certificate. Right: The University of Manchester and Dalton Nuclear Institute team with their award

In October, the 2023 Bhattacharyya Award was jointly presented to two academia–industry partnerships: Loughborough University and adidas, and the University of Manchester and the nuclear decommissioning sector.

The Loughborough University and adidas partnership has developed sports equipment and clothing for improved performance, safety and inclusivity. This has brought iconic products to market such as World Cup footballs and more advanced cricket helmets that have eliminated facial injuries among professional helmeted batters.

The University of Manchester's work with the nuclear decommissioning sector has provided expertise for quicker, safer nuclear decommissioning. Since 2002, the government has focused on cleaning up the UK's complex nuclear legacy. The Dalton Nuclear Institute coordinates the UK's most comprehensive nuclear academic community at the university to deliver skilled people, impactful research and support for government policy development.

Funded by the Department for Science, Innovation and Technology, the Bhattacharyya Award is awarded annually to a UK university or college that has demonstrated a sustained, strategic industrial partnership in any academic discipline that has benefited society and deserves national recognition.

WORLD'S FIRST HEART SIMULATION GOES LIVE

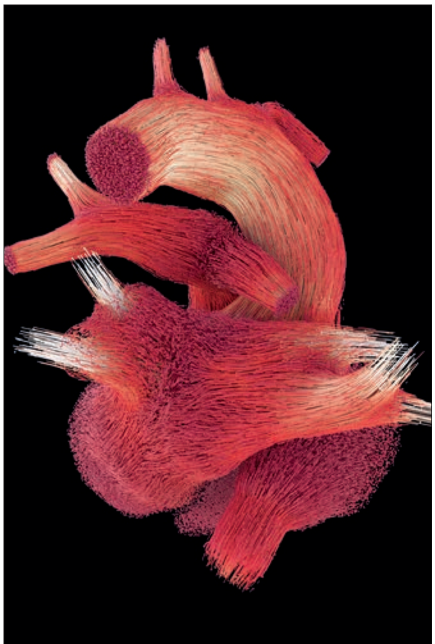
In November, the Science Museum unveiled a digital simulation of a beating human heart in its Engineers gallery.

Created by bioengineer Dr Jazmin Aguado Sierra using scans of her own heart, it shows the complex interactions between electrical impulses, muscle contraction and blood flow in the heart, made possible using supercomputer power.

Dr Aguado Sierra used her own data captured from sources including electrocardiographs that measured electrical impulses and magnetic resonance imaging (MRI) scans of her heart tissue. The large data sets were then inputted into mathematical equations that described her heart's workings and her virtual heart was reproduced by MareNostrum 4, a high-performance supercomputer based at Barcelona Supercomputing Center.

The new model builds on earlier research and allows us to better understand this vital organ. The calculations can be adjusted to simulate different heart conditions, showing why a heart beats too fast, too slow or irregularly. Doctors and researchers can also test treatments before they are used on patients, and in the future, digital twins of entire bodies could be made, transforming how we could predict, diagnose and treat illness.

Dr Jazmin Aguado Sierra said of her virtual heart: "The first time I saw my heart pumping it was fascinating!… Supercomputing is changing the way modelling works and having access to my own data enriches the model that much faster. The more I learn about my heart, the more I will be able to produce new protocols or new tests, which is exciting for the future of predictive and personalised medicine."



Still from the Virtual Heart model showing the way blood moves through the organ © Science Museum

MOTORSPORTS AWARDEES ANNOUNCED AT SILVERSTONE

In October, the Royal Academy of Engineering announced the first Black or mixed Black students who will receive MSc scholarships in motorsport engineering or associated disciplines, supported by Sir Lewis Hamilton HonFREng's charitable foundation Mission 44.

The five successful applicants will study at Cranfield University, Kingston University London, Oxford Brookes University, and Cardiff University.

Each student will receive £25,000 to cover full tuition fees and living costs. Wraparound support includes networking events and motorsport experiences, with the objective that within two years of completing the MSc most, if not all, will be employed in engineering – with the majority in motorsport and Formula 1. Sir Lewis and Mercedes-AMG PETRONAS F1 Team provided inaugural funding to the programme, and it is now continued through the work of Mission 44.

The five awardees who have received Motorsport MSc Scholarships

All five awardees attended a first networking event at Silverstone Museum. They met with staff from the Academy and Mission 44, had a Q&A session with engineers from the Mercedes-AMG PETRONAS F1 Team, toured the museum, and had sessions on the simulator.

GET INVOLVED IN ENGINEERING

© Science Museum Group

SPIRIT OF INNOVATION

Science Museum, London

The world's fastest all-electric aircraft, the Spirit of Innovation, is now on display in the Science Museum's Making the Modern World gallery, which presents advances in science and technology from the birth of the Industrial Revolution to the present day. The aircraft holds the all-electric aircraft world record for the highest top speed over three kilometres and also set a new record for the fastest climb by an electric aircraft to three kilometres.

www.sciencemuseum.org.uk

CLIMATE SCHOOLS PROGRAMME

From January 2024

Nationwide

EngineeringUK has launched a brand-new pilot programme for schools. It is designed to help students aged 11 to 14 explore solutions to tackling climate change and discover how engineers and engineering and technology are a key part of this. To find out more and register your interest, visit

climateschoolsprogramme.org.uk

Photo by Shawn Henry on Unsplash

SKATEBOARD

Until 2 June 2024

Design Museum, London

This exhibition chronicles the history of skateboard design from the 1950s to the present day, from homemade, humble beginnings to today's professional and technologically advanced models.

designmuseum.org

ENGINEERING REVIEW OF THE YEAR

4 December 2023

Online

Join a panel of experts as they dissect the big stories of 2023 from an engineering point of view – everything from AI to engineering for net zero and the exciting innovation happening all over the UK and beyond. It's free to attend but to register, visit

www.raeng.org.uk/events

HOW I GOT HERE

Q&A

KHADIJAH ISMAIL
AEROSPACE ENGINEER

Khadijah in Nepal at the site of a solar grinding mill project © Khadijah Ismail 2021

After completing a degree apprenticeship with BAE Systems, Khadijah Ismail has turned her hand to writing STEM children's books to inspire the next generation of engineers.

WHY DID YOU BECOME INTERESTED IN SCIENCE AND ENGINEERING?

I've always been captivated by aircraft, and that childhood wonder never really left me. It felt natural to channel that passion into a career in aerospace engineering. The thrill of understanding the intricacies of flight and the mechanics behind it was intriguing.

HOW DID YOU GET TO WHERE YOU ARE NOW?

I took a nonconventional path. Instead of the traditional academic route, I embarked on a degree apprenticeship with BAE Systems. This provided me with invaluable learning experiences and exposure to different facets of engineering. Over the past six years at BAE Systems, I've rotated among various teams, delving into different parts of the engineering lifecycle and truly comprehending systems thinking.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

There have been several milestones in my career, but two stand out. First, contributing to the PHASA-35 project, which is an ultra-lightweight, high-altitude, pseudo-satellite, uncrewed aerial system that is powered by solar energy. It will provide an alternative for Earth observation and satellite communications. The second is being a part of the Kaan project in Turkey to design and develop an indigenous fifth-generation fighter jet for the Turkish Air Force. Outside of my core job, I had the privilege to travel to Nepal (thanks to funding from the Royal Academy of Engineering's Engineering Leaders Scholarship programme), to work on solar microgrids. I'm also currently working

QUICK-FIRE FACTS

Age: **24**

Qualifications: **degree in aerospace engineering (through apprenticeship with BAE Systems)**

Biggest engineering inspiration: **the brilliant engineers I work with daily**

Most-used technology: **Magicdraw by Dassault Systems**

Three words that describe you: **motivated, enthusiastic, driven**

on STEM books for children, aiming to inspire the next generation, which are available on Amazon.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

For me, the beauty of engineering lies in its ability to reduce complexity and make sense of the intricate. I cherish the opportunity to think abstractly, employ model-based systems engineering approaches, and contribute to projects that have a tangible impact on our world. But it's more than just the technical bits – it's about the people I work with, the shared laughter over a coffee break, and the collective cheer when we crack a tough problem.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

As a mission systems engineer based in Turkey, my day revolves around employing systems thinking to navigate challenges. I frequently use Magicdraw by Dassault Systems, a software toolset that aids in understanding and addressing complex engineering problems through a model-based approach.

Illustration featuring the characters in *The STEMventurers* © Khadijah Ismail

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

There's magic in engineering, in creating, in building. Embrace every learning opportunity that comes your way. Engineering is not just about technical know-how: it's about understanding the bigger picture, collaborating with others, and being persistent in the face of challenges. Remember, unconventional paths often lead to the most rewarding experiences.

WHAT'S NEXT FOR YOU?

I'm excited about the continuous growth and learning opportunities that lie ahead. I aim to further my contributions in aerospace engineering and expand on my passion project: the STEM books for children. I believe in empowering the next generation with knowledge and inspiration.

OPINION

HOW TO ENGINEER RESPONSIBLE AI

The public launch and mass uptake of ChatGPT in 2022 marked a watershed moment in the history of artificial intelligence (AI). ChatGPT, and other chatbots like it, increased the accessibility of generative AI to a wider public and brought more acute attention to AI-powered applications. The Royal Academy of Engineering's *Engineering responsible AI* blog series is exploring themes around developing and deploying AI safely and ethically. Here, *Ingenia* hears from two of the experts involved in the series.

Data and AI product engineer, Charlette N'Guessan, shares her thoughts on how generative AI can be more inclusive.

The rise in popularity of ChatGPT has led to more people paying attention to AI, and we've seen a proliferation of generative AI tools. I hope this creates an opportunity for people to build AI models and find AI solutions that make a real societal impact.

I also hope that relevant stakeholders involved in the production of AI solutions, like innovators, use this opportunity to be conscious and responsible as they think about how generative AI can make a positive impact at a local and global level. We need to build solutions that can address challenges by leveraging the technology in the right way. Experience proves that when people build AI models like generative AI quickly, building for the sake of building, they are unlikely to spend a lot of time on things like the ethics surrounding data collection and data privacy. So, we should make sure that whatever we build, it's not just to fit into the AI trends, but to meet people's needs while following certain principles.

FEARS ABOUT THE FUTURE OF GENERATIVE AI

We currently face a range of challenges, and one area of fear is about misinformation, which is amplified by AI-generated content that often includes inaccuracies. The alarming aspect is the rapid and widespread sharing of such content, as individuals often neglect to verify the credibility of the sources they encounter online. It's particularly tough to distinguish between true and false information when it comes to generative AI. Indeed, generative AI can generate highly convincing and coherent content that is difficult to differentiate from human-generated content.

As an AI product engineer, I also worry about accountability as we continue advancing this technology. For instance, there's growing criticism over biases in AI models, the lack of diverse data and data security, among other issues. I believe that we should also ask, who is accountable for that? Right now, AI regulations are still nonexistent in many countries – especially in most African countries – and there is a tendency for innovators to avoid responsibility by hiding behind the system and deferring accountability.

SAFE AND IMPACTFUL USE OF AI

In the world of AI, various stakeholders play significant roles, including innovators, regulators, and researchers. Each of these groups must bring their attention to specific questions.

For instance, for researchers, the crucial questions are: "how can my research help find practical ways to solve local and global problems?" and "what is the long-term impact of my AI research on society?".

For innovators, the questions to ask are: "what specific problems am I addressing? How can I ensure that my AI model adheres to existing regulatory standards? Does my AI algorithm demonstrate the reasoning behind a given model's decision-making?".

Regulators need to recognise the importance of engaging with various stakeholders, especially those involved in the development of AI models, to enhance the synergy between regulations and innovation.

It is crucial to ensure that AI regulations do not act as barriers for innovators, but instead establish a secure framework within which innovators can advance their AI solutions.

All parties, including researchers, those deploying the technologies, regulators, and policymakers, must work together to ensure the safe use of generative AI. Generative AI comes from long research efforts, and like any new technology, collaboration is vital once we understand its initial outcomes. The reality is that generative AI is new, and some experts are still struggling to control the spread of the use of generative AI models. This is why researchers must keep conducting rigorous studies to uncover potential risks, vulnerabilities and biases. This will also help to discover new relevant patterns to consider in the production of generative AI.

People deploying generative AI, like entrepreneurs and businesses, have the opportunity to enhance existing models via the process of fine-tuning AI algorithms. They also provide these AI models to the market and create ways to test them and get user feedback. This is important for ensuring accuracy and tracking the impact of generative AI models.

Regulators and policymakers must work together to create laws for generative AI and make sure everyone follows them, which helps ensure safe use of generative AI.

BIOGRAPHY

Charlette N'Guessan is a data and AI product engineer with experience in building AI ventures for the African market. In 2018, she co-founded and led the development of the BACE API, an AI-powered remote identity verification system using facial recognition to combat online identity fraud and strengthen the digital identity system in Africa, which won the 2020 Africa Prize for Engineering Innovation. Her current focus is centred around researching ways to address data biases in AI solutions intended for the African market.

Professor Lionel Tarassenko CBE FREng FMedSci, Professor of Electrical Engineering, University of Oxford, discusses what generative AI's potential uses and drawbacks might mean for us.

There are many useful applications of generative AI (also known as large language models), but there is a lot of confusion among the general public about what generative AI is and what it can do. ChatGPT seems to behave like an intelligent human being when a user interacts with it; it appears to understand what you are asking or saying to it, but it does not – it is just an extremely smart predictive text system.

Part of our role as engineers and computer scientists is to explain to the general public how large language models (LLMs) work.

For context, when an LLM works with text, the first step is to tokenise it, which maps words and word segments to a set of tokens, a set of numbers. An LLM learns associations between tokens from scratch using what is called an attention mechanism during its training phase by going through billions of training runs. By doing that over and over again, it gradually learns how words relate to each other, and which words to associate with others in the same sentence to make connections based on existing patterns. It is not learning the meaning of words, but rather learning the statistics associated with a language.

My expectation is that generative AI will be transformative across a range of sectors including healthcare. But to access that potential we must have the right data. We have enough healthcare data within the NHS, but the issue is that it's not aggregated properly, which limits our ability to leverage the value of generative AI for healthcare.

For almost any disease, early detection improves outcomes. Given the right data to train these LLMs, earlier detection will become possible for a vast range of diseases. There are predictive tasks we couldn't do before that will become possible through the development and deployment of generative AI.

FEARS ABOUT THE FUTURE OF GENERATIVE AI

One of the issues is the trustworthiness of input data. Training a generative, pre-trained transformer (GPT) using the data readily available on the internet should be avoided for healthcare applications. If you are trying to detect cancer early, you need oncology textbooks, the last 10 years of research papers in this domain, and electronic patient records to develop your own training database to train the generative AI model.

Capacity is also a concern. There are probably six big tech companies in the world that can duplicate what OpenAI has achieved with ChatGPT (GPT-3.5 and GPT-4). Huge amounts of resources – billions of dollars, huge amounts of electricity, huge amounts of time – are required to compete with these companies. I am concerned about the future of AI being in the hands of big tech companies in the US and China (probably the only two countries that have the right scale) and the potential lack of control from stakeholders to apply oversight, starting with governments. The recent AI Safety Summit at Bletchley Park is a first step in the right direction.

Another worry with LLMs is that certain tasks can only be achieved with a large enough model and huge amounts of training data. For example, when conversing in French or German, ChatGPT would only assign grammatical gender in its outputs randomly. However, once GPT-4, a bigger model, was trained (in exactly the same way), it became 100% accurate in the assignment of grammatical gender. This is because GPT-4 has billions more weights, with a bigger training dataset, and enough free parameters to achieve this task. But we do not fully understand why GPT-4 has learned this while GPT-3.5 did not. An LLM must be large enough before certain emergent properties arise, but we do not know why and that is a concern.

SAFE AND IMPACTFUL USE OF AI

The main question should remain: where is the human in the loop? If you want to use these AI tools safely, they still need to be validated by a human being. For example, with healthcare, when you are predicting the outcome for a patient, you still need the doctor to be involved to validate the prediction from the AI model making that prediction. That involves asking, among other questions, "What was the training set and is there any bias in it?".

A further question when considering the possible dangers of AI tools is, are there any actuators connected to their outputs? If the output is simply text or images on a screen, then it is easier to control harmful effects, but if the AI system is connected to actuators that generate physical actions, we need tighter regulation to ensure that these systems are safe.

Although there may be a sense that we are having a conversation with an LLM, the chatbot does not understand in the way that people do. Some descriptions used in relation to LLMs are not helpful (even the use of the word 'hallucination', as it anthropomorphises the LLM), and some of the hype is generated because people do not fully understand what LLMs do.

An interesting aspect of AI-enabled products is that, by using a tool like ChatGPT, a not very efficient worker can be made much more efficient – while an efficient worker will only be made slightly more efficient. The use of the tool effectively reduces the gap between those at the top of the profession and those who are further behind – an interesting development to think about in terms of jobs and the future of work.

Part of our role as engineers and computer scientists is to explain to the general public what an LLM does. People may unintentionally be misled about what generative AI is and those of us regularly working with these new technologies can help bring clarity to the discussion.

BIOGRAPHY

Lionel Tarassenko is a pioneer in the application of machine learning technologies in clinical care settings. His research has created new methods for assessing patient deterioration and chronic disease management. One of his machine learning systems designed to monitor critical care patients was the first of its kind to gain FDA approval back in 2008.

These pieces were adapted from the Engineering responsible AI *blog series. To read them in full and hear from other experts in AI, please visit* ***raeng.org.uk/engineering-responsible-ai***

ENGINEERING SWARM ROBOTICS

Illustration for *Ingenia* by Benjamin Leon

As an engineer and nature-lover, Dr Anna Ploszajski has always been fascinated by biomimicry: taking inspiration from nature to improve our human-made world. Here, she explores the engineering that goes into copying one of nature's finest spectacles, and some of the surprising applications possible when robots work together.

Did you know?

- Swarms in nature (and robotic swarms, too) don't have any kind of central coordination, or rely on members of the swarm playing a different role from the others (such as being a leader)
- The robots that are being trained to become members of swarms are increasingly being trained using AI deep learning, a type of machine learning
- Swarm robotics are being proposed for search and rescue after natural disasters, by militaries, and even to battle wildfires

Every winter evening, hundreds of thousands of starlings swarm from across Sussex to roost on Brighton's piers, forming dark, liquid shapes across the sky. This sight – also visible in many other places in the UK over winter – is a grounding reminder of the natural world's beauty and power.

Murmurating starlings, as well as swarming insects and schools of fish, are fantastic examples of the inspiration for a branch of engineering called swarm robotics.

This is the approach of using large numbers of robots that coordinate with each other to create a moving mass whose behaviour is more than the sum of its parts.

FROM SIMPLE TO COMPLEX

Swarming is what's known as an 'emergent' behaviour in mathematics. It's an example of a self-organising system, where simple rules followed by a group of individuals give rise to a larger mass that behaves as one. Importantly, it does not involve any central coordination or instruction. This also means the swarm doesn't rely on any member playing a different role from the others, such as being a leader (although you can have a replaceable leader, as with a V formation of flying geese). Swarms can therefore cope with the removal or addition of individual members without it majorly impacting the whole.

Computer models of swarms were first developed in the 1980s by Craig Reynolds, a computer programmer from Chicago. While living in Los Angeles, Reynolds made a computer program about swarming 'boids', which simulate a flock of birds.

"As a child, I was fascinated by what I would now call natural complexity: the turbulent shape of clouds, plant shapes, ant colonies, bird flocks," says Reynolds, of his early inspiration.

"In college [in the 1970s], I studied programming and graphics, and started thinking about such things through the lens of software simulation models."

Reynolds was inspired by Braitenberg vehicles. These very simple machines were first proposed by (and named after) the neuroscientist, Valentino Braitenberg, in the early 1980s. They move in response to signals (usually a light source) detected by onboard sensors.

"Watching a flock from the outside seemed too complicated. But when I imagined it from a bird's perspective it seemed much less so. It seemed clear that as a bird, I would want to make small incremental adjustments in my speed and heading," explains Reynolds. "If I got too close to a nearby flockmate, I'd want to gently steer away from them. To not get too close in the future, I'd want to steer in roughly the same direction as nearby flockmates. To stay with my flock, if I were on the outside edge, I would steer gently in, toward my nearby flockmates." As it turned out, complexity could emerge from these surprisingly simple rules.

"I carried that idea in my head for a while. I thought those three rules (what I now call separation, alignment and cohesion) were necessary but wasn't sure if they were sufficient. In 1986, I finally tried to implement it. Fortunately for me, those three rules produce flocking."

BIOMIMICRY

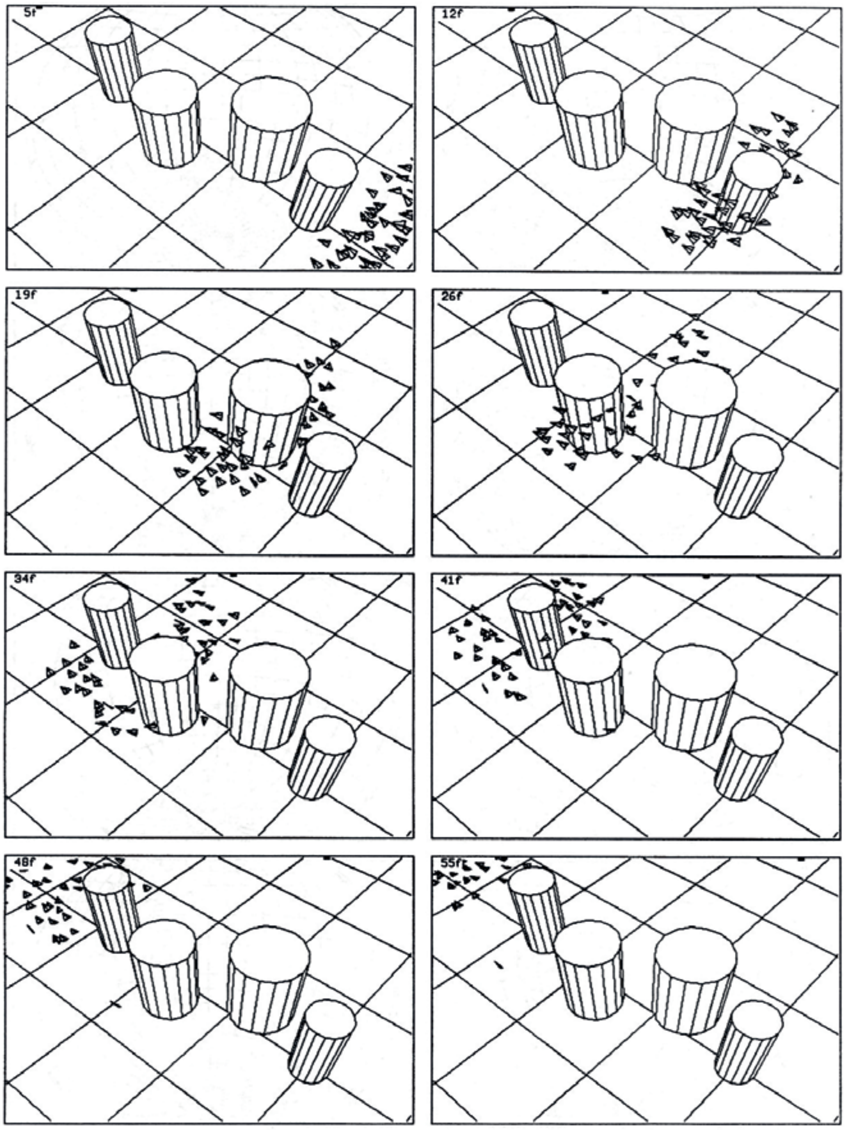
Some of Anna's favourite examples of biomimicry are:

1. Superhydrophobic coatings that emulate the waxy, hairy surface of a lotus leaf to make extremely waterproof and self-cleaning surfaces.
2. Wind turbine blades made more aerodynamic by copying the serrated edges of humpback whale fins.
3. Solar panels with double the efficiency thanks to engineers copying the geometric surfaces on a butterfly's wings.

EMERGENCE

Other examples of emergence are:

1. Water molecules bonding together in formations that self-assemble under the right conditions to give rise to complex and symmetrical patterns of snowflakes.
2. Neurons in the brain that fire electrical signals individually, but together give rise to consciousness.
3. Life itself is an emergent property of carbohydrates, lipids, proteins, and nucleic acid molecules forming the simple structural building blocks of living things.



Screenshots from Craig Reynolds' work simulating swarms, in about 1987

THE PSYCHOLOGY OF BRAITENBERG VEHICLES

Part of Braitenberg's theory was how the vehicles exemplify the human tendency to anthropomorphise non-sentient machines. This is because humans observing robots being repeatedly drawn to or avoiding a stimulus can easily impart behavioural interpretations such as 'aggressive' or 'cowardly' onto them.

"The unpredictable, improvisational nature of flock motion was a pleasant surprise to me," says Reynolds. "It made the simplistic simulations feel much more 'alive' than I expected."

But while the idea sounds relatively straightforward, implementing it had its challenges.

"A problem I did not anticipate was the difficulty of tuning the model's parameters. It had about 10 parameters, control knobs, to adjust," he explains. "They all interacted (nonlinearly), so adjusting one always meant adjusting others, which meant adjusting others. It took many, many tests to converge on the desired type of motion."

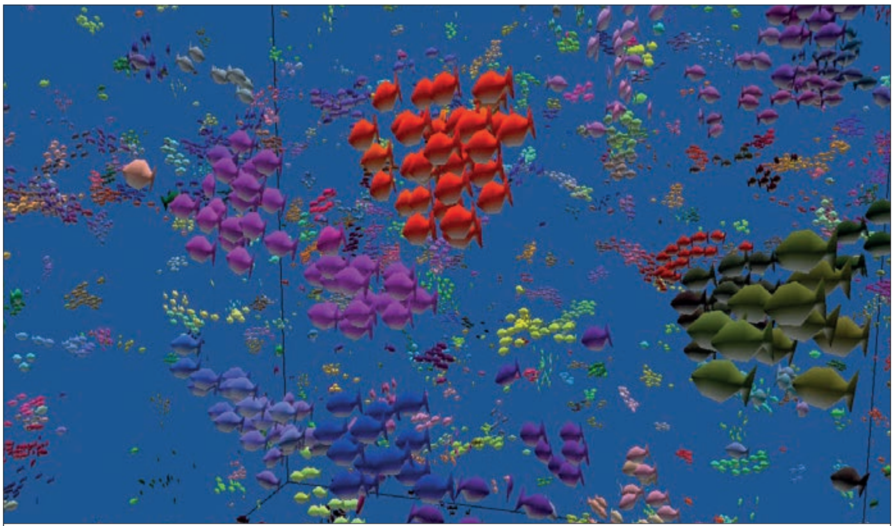
While this means essentially any type of motion was possible, it was also deeply complex to do. So, researchers have been automating the process using optimisation techniques, such as algorithms and machine-learning approaches.

SIMULATING SWARMS IN MOVIES AND GAMING

Reynolds has since spent a large part of his career refining these models, including adding complications such as obstacles for the boids to avoid, or targets for them to reach. His career has led him to work in all sorts of applied areas, from graphics for gaming and the films *Tron* and *Batman Returns*, to autonomous vehicles.

"In feature animation, use of these techniques generally has to do with background action: crowds in cities, herds of animals out in the wild, and battle scenes," says Reynolds. "In games, the difference is that everything must operate in real-time (easy [today], quite challenging a decade or two ago) and the members of the crowd (nonplayer characters) usually need to react to the player's character."

Reynolds also developed virtual simulations of cars, technology that would lay the groundwork for that used in autonomous or driverless vehicles. "I was creating the dynamic elements in urban and highway environments, to which the simulated car under test needed to react. This was primarily vehicle traffic on the roads, and to a lesser



Reynolds developed simulations for the PlayStation 3. The PSCrowd Chameleon Fish demo simulated 10,000 schooling fish at 60 frames per second

extent, pedestrians on sidewalks and crosswalks," he says.

While there was a degree of crossover with his previous projects, these simulations had to go further still. "The crowds were quite similar to game worlds. The vehicle agents had [very] different 'locomotion' styles due to their mechanics: turning radius, stopping distance, and the like, in addition to being much larger and more dangerous."

This illustrates one key challenge in the field of swarm robotics: how to bridge the gap between simulation in the virtual world and real robots in the physical world.

SWARM INTELLIGENCE

Moving swarms from the digital world into a physical environment introduces lots of extra challenges, quickly pushing the limits of these so-called 'classical' algorithms. This is especially true if there are many robots involved.

So, today's models for swarm robotics are being informed by artificial intelligence (AI) – a field called swarm intelligence. It allows each robot to interact locally with one another (as in the early models), but also for members of the swarm to quickly learn about the surrounding environment and adapt to changes in it.

Professor Amanda Prorok at the University of Cambridge uses neural networks to train robotic swarms. She explains the key training paradigms: imitation learning and reinforcement learning.

"In imitation learning, you show the robot what it's supposed to do in given scenarios… and the robot learns to copy it. And in reinforcement learning, you reward the ideal behaviour when the robot gets something right. For example, if you want a robot to find an exit of a maze, you can tell that robot, 'Hey, when you find that exit, I'm going to reward you.' Over time, it learns the right behaviour."

This 'training' would take too long in the physical world, so the robots are often 'trained' in a simulated, computer world, and then this learning is transferred to the physical robots.

But this leads to another problem. "As we go about deploying our robots in the real world, we encounter something called the simulation-to-reality gap. Because the world that the robot encountered in simulation is not the same [as] the real world," she says. "No matter how hard you try, it's very hard to create photo-realistic environments in simulation with the right kind of lighting and everything… so when you give the robot its sensor, it's suddenly encountering sunlight, and cloudy skies… and it doesn't know how to deal with those conditions." This particular case applies to robots with camera sensors. Other types of sensors, for example sonar or infrared, can suffer from other distortion factors.

According to Professor Prorok, researchers will instead pre-train the robot in simulation, and then fine-tune the behaviour of the actual robot in a "safe kind of sandbox-type situation", such as in the lab. With this approach and the help of clever algorithms, robotics labs around the world are making solid progress towards addressing the many technical challenges that swarm robotics face.

That's all well and good for individual robots, but how does it map onto swarm control? As Professor Prorok explains, a decentralised model is most like natural swarms seen in nature. In such a scheme, there's no overarching, 'mastermind'-style control system. Each robot governs its own behaviour, with input only from nearby robots. This is how it works in the Prorok Lab's research, too – each robot in a swarm is responsible for its own behaviour.

REAL-WORLD SWARMS

There are many exciting real-world applications for swarm robotics. Militaries have made some of the most notable advances in the area. US government agencies, such as the Defense Advanced Research Projects Agency (DARPA) and the Navy, are investing in developing swarms of uncrewed aerial vehicles and boats.

Civilian applications are also taking flight. Search and rescue missions often demand access to difficult-to-reach places, exploring unknown environments and solving complex geometrical problems (such as systematically searching a collapsed building). Swarms of small flying or ground-based robot systems are well-suited to such tasks. London-based startup Unmanned Life is one company developing AI software to manage drone swarms for search and rescue tasks, as well as for commercial security such as in ports. Similarly, Southampton-based Windracers is working on autonomous drone swarm technology to detect and fight wildfires.

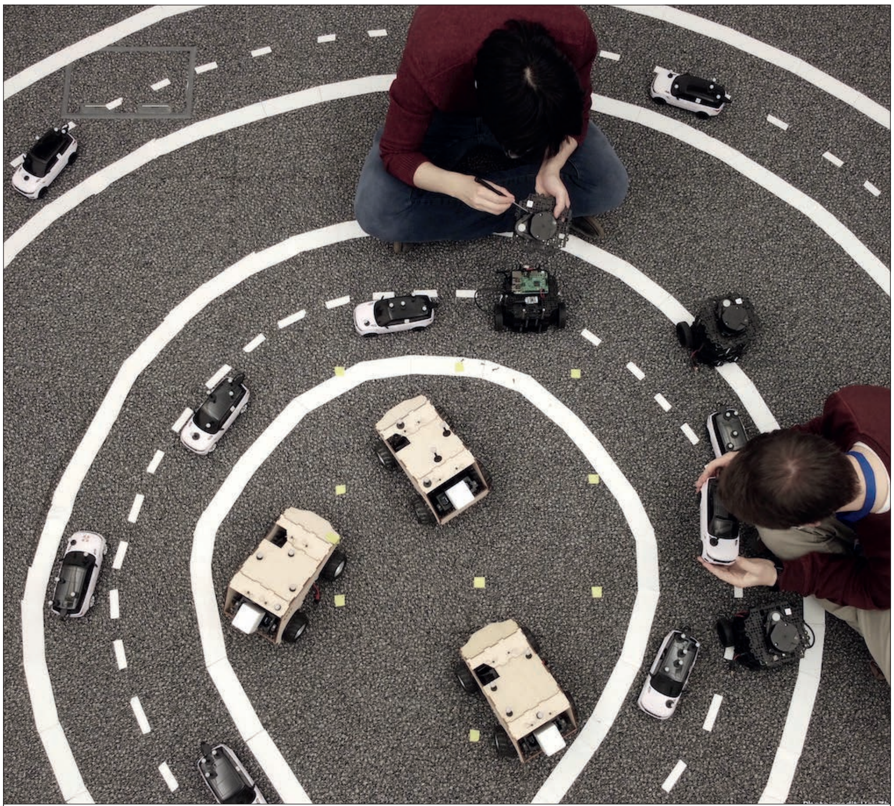
In a project led by Oregon State University, researchers are developing swarms to explore hard-to-reach underwater polar environments, where communications with the surface are limited. They hope that sending them to places such as the cavities underneath ice shelves will shed light on how ice melt contributes to sea level rise.

Autonomous swarms have even been suggested for manufacturing, known as swarm 3D printing, and medicine, with microscopic swarms that could deliver pharmaceutical or surgical interventions inside the body.

However, before these exciting applications materialise, engineers must address key challenges in the field such as keeping costs down, poor battery life and miniaturising the individual robots. Researchers share the goal of keeping the individual robots as simple and cheap as possible, to maximise scalability and power efficiency. Specific challenges such as programming adjustments in flight for drones blowing each other off-course also plague researchers, but programming involving AI is helping refine these systems.

AI, too, comes with its own problems. "I think one thing that people don't really realise is that the larger the models are, the less interpretable they are, and the less we can verify and certify their behaviour. So it's really difficult for us to guarantee what the model's going to do in certain situations," says Professor Prorok.

She draws a parallel with large language models such as ChatGPT, and the unexpected ways they can behave. "It's the same thing with robots. But the thing with robots is, now we're not talking about virtual harm, we're talking physical harm, right? They're moving in a physical world. Their actions are not words, their action is motion. So, I think we have to be a bit careful about that."



In one of the Prorok Lab's projects at the University of Cambridge, the team used AI-trained miniature car robots as a model for autonomous vehicles © Prorok Lab

THE ENVIRONMENTAL COST OF AI

Environmental harms, too, are a concern of Professor Prorok's. "People don't realise how costly AI is from an environmental point of view. It costs a lot of electricity to train one ChatGPT model. So I think we need to think a bit more about, when you're embarking on training a really big model, is it worth burning down half a forest to do that?" she says.

"I think reuse and recycling of models needs to be taken more seriously, because it's just not sustainable for the planet. GPUs [graphics processing units – powerful computer chips often used for scientific and AI applications] are made of precious metals, electronics are scarce, we're blowing up mountains all over the world to generate these things, let alone the electricity you then need to run them, and cool the buildings they're in… people don't realise this backstage part of AI. We need people working in parallel to find solutions to those aspects, too."

BIOGRAPHIES

Amanda Prorok is Professor of Collective Intelligence and Robotics in the Department of Computer Science and Technology at the University of Cambridge. Her mission is to develop solutions for collective intelligence in multi-robot and multi-agent systems. This research brings in methods from machine learning, planning and control.

Craig Reynolds is an unaffiliated researcher and retired software developer. He is best known for the 'boids' model of flocking and similar collective motion, and has researched the evolution of camouflage. His research publications have been cited 18,000 times. His feature film work won AMPAS's Scientific And Engineering Award in 1998.

The foams used to combat jet fuel fires at air bases have been a major source of forever chemical pollution worldwide
© Shutterstock

HOW TO MAKE WATER FOREVER CLEAN

Move over, microplastics, there's a troubling new pollutant in town. Used to manufacture iPhone chips, waterproof trousers and many more everyday items, forever chemicals have been implicated in a worrying range of health conditions. Beverley D'Silva explores the technologies engineers are developing to safely capture and destroy forever chemicals for good.

Did you know?

- While they have many useful applications, forever chemicals accumulate in the environment and in our bodies (and are found as microplastics, too)
- Governments around the world are moving to set new legal limits on the acceptable concentration of forever chemicals in drinking water
- Manufacturers are phasing out PFAS and finding alternatives for them in applications such as waterproof clothing

Chances are, you've heard of 'forever chemicals' – and have probably come across them in daily life. Just this year, researchers have found them in pregnant women's blood, on organic kale, and even in toilet paper. This comes alongside a growing pile of epidemiological evidence that exposure to forever chemicals could be implicated in "a variety of health effects, including altered immune and thyroid function, liver disease, lipid and insulin dysregulation, kidney disease, adverse reproductive and developmental outcomes, and cancer".

In chemistry terms, forever chemicals are known as per- and polyfluoroalkyl substances (PFAS). They are a group of synthetic chemicals with atoms of fluorine (the F bit), and other elements strung along a chain of carbon atoms. There are thousands of PFAS, some of which have been around since the 1940s.

The strength of the carbon–fluorine bonds makes these chemicals very versatile – for example, they are oil- and water-repellant, and heat-resistant. Thanks to these properties, manufacturers have used them in many things, from foams for firefighting, to waterproof clothing, nonstick cookware, coatings inside pizza boxes, and cosmetics. They're even essential to the semiconductor industry. However, the properties that make them so useful in their intended applications also make them persistent in the environment – and dangerous to wildlife and people.

As the carbon–fluorine bond in PFAS molecules does not occur in nature, there is no known biodegradation pathway. PFAS can find their way into the water that we drink and get into our bodies, and are also difficult to remove with conventional water or soil treatment technologies. With unsafe levels detected in drinking water in the US and Europe, the race is on to solve the PFAS problem. That means safely capturing and removing the molecules and then destroying or storing them.

SEPARATION AND BUBBLES

Firefighting foams have caused some of the most significant environmental leaks of PFAS. Now largely phased out, perfluorooctane sulfonate (PFOS) was a component of aqueous film-forming foams (AFFFs), used extensively to put out fires in airfields.

UK- and Germany-based firm Cornelsen has been targeting PFOS for more than 10 years, starting out with airfield remediations of jet fuel fires. Now, the company offers AFFF decontamination of fire trucks and appliances, in-situ remediation, and industrial water treatment systems.

"There was a lot of it [PFOS], and we tried treating it conventionally, with

THE PROBLEMS WITH REMEDIATING PFAS

Chemical engineers are following several hopeful options for removing PFAS from water, but it's no easy task. Even detecting them in the first place is made harder by our limited understanding of this tricky chemical family. According to the American Water Works Association, only a relatively small number of PFAS can be reliably measured. The number of PFAS whose treatment has been rigorously studied in peer-reviewed research is even smaller.

Compounding this is the vast list of unknown PFAS created by manufacturers. Many are still under patent, with water treatment labs unable to access standards to allow them to look for these. "We see things happening in treatment plants that show elevated levels of a PFAS, but we have no way of analysing it and quantifying it," says Matt Ingram, from environmental remediation and water treatment firm Cornelsen.

In the UK, the guideline limit in drinking water is 100 nanograms per litre, per specific PFAS compound. (This is two thousand times less than a teaspoon dissolved in an Olympic swimming pool.) The Royal Society of Chemistry has recently suggested this should be reduced to 10 nanograms per litre. "You have people saying we can tackle PFAS with activated carbon, for example, but you need more and more [storage] vessels in order to get to the very low discharge limits," says Henrik Hagemann, CEO and Co-Founder of Puraffinity, a UK startup that is developing PFAS remediation technology.

The length of the PFAS molecule's carbon backbone is also important. At the turn of the millennium, regulators raised the alarm about the degree to which PFAS molecules with long carbon chains were accumulating in people and the environment. Global chemical manufacturers switched to molecules with shorter chains. However, these new PFAS molecules containing shorter carbon chains are more water-soluble, and as a result, harder to extract than short chains.

On top of this, PFAS concentrations can be so low that it can be difficult to measure the effects of treatment.

In tackling forever chemicals, Puraffinity, a green tech company based in the UK, has developed smart granules that can selectively remove PFAS from a contaminated solution

adsorbent material. We quickly realised that was unsuccessful, incredibly expensive, and not very effective. It also produced a huge secondary waste stream," says Matt Ingram, general manager at Cornelsen.

The team focused on separation approaches (see 'How to extract forever chemicals from water'). Working with the German applied research institute, Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, Cornelsen came up with PerFluorAd. When added to contaminated water, this cost-effective biodegradable agent causes dissolved PFAS (including PFOS) to separate out in tiny solid clumps (precipitate) that can be filtered out of the solution.

In the past five years, the company has been rinsing out firefighting appliances contaminated with PFAS. Demand in Germany has been consistently high and is growing in the UK. Ingram says the approach removes over 99% of longer chain PFAS present, including PFOS.

Later, the company came across a sustainable PFAS remediation technology developed by Australian company Epoc Enviro. Surface-active foam fractionation (SAFF) uses rising air bubbles to remove PFAS contaminants from contaminated water. PFAS molecules have both water-loving and water-hating components, making them a 'surfactant' (like soap). Because of this, the PFAS stick to the surface of bubbles before they rise to the surface.

"It foams PFAS out of the water, then concentrates that foam many times further. We end up with a very small amount of liquid waste, and the water passes through clean the other side," says Ingram.

According to Ingram, PerFluorAd and SAFF are the only technologies that don't create a large secondary waste stream. "PerFluorAd is dosed into the water and removes the PFAS as a solid. We then filter that out. So, the waste stream is as small as the amount of PFAS in the water."

However, a major challenge for Cornelsen has been getting regulators to approve the technology, resulting in significant delays. "Scaling up has also been hard, in terms of both finance and establishing constant stable treatment," says Ingram.

DESIGNER GRANULES

In tackling forever chemicals, Puraffinity, a green tech company based in the UK, has developed smart granules that can selectively remove PFAS from a contaminated solution. Puraffinity's CEO and Co-Founder, Henrik Hagemann, was in an Imperial College London team in 2014 that entered an MIT competition to find solutions to pressing environmental challenges. "The issue that came up again and again was contaminants

EXTRACTING FOREVER CHEMICALS FROM WATER

Water treatment approaches to remove PFAS generally fall into two categories. The first is adsorption, where they 'stick' to a solid substrate mixed into the contaminated water. The second involves separating them from the solution.

Adsorption usually deploys porous materials to maximise the surface area that the PFAS can stick to. The process often uses particles of processed charcoal or micrometre-sized polymer beads. However, neither approach removes all types of PFAS and both can get clogged up with other (non-PFAS) molecules. Once finished with, the porous material is then fully saturated with a high concentration of PFAS. This secondary waste stream must be safely stored or destroyed.

Cornelsen's remediation plant, which uses separation approaches © Cornelsen Ltd in water," says Hagemann. "We kept being asked about these fluorinated compounds, so we began looking into using activated carbon materials."

Back then, "there wasn't even a name for PFAS", he says. "We learnt about them from customers with contamination issues, like an airport that needed to clean up run-off water from firefighting foam drills, and the oil and gas sector that used [PFAS such as PFOS] to inhibit fires on oil-drilling rigs."

Having raised £20 million, the company has spent nearly £13 million developing this smart material for environmental remediation and decontaminating industrial manufacturing facilities, commercial airports and military bases. "At first, we focused on developing a membrane, but we found it got blocked up," he says. "So, we switched to a granule… You can just dump it in, like a pellet into an industrial-sized media bed."

Unlike conventional 'blanket' approaches, Hagemann and his team tailored the granule to selectively remove different types of PFAS. To do this, they developed special peptides mimics – short chains of amino acids, the building blocks of proteins – that preferentially stick to different PFAS molecules. They then took these peptide mimics and coated the granules with them so that, in a contaminated solution, PFAS molecules would attach themselves to the coated granules.

Additionally, when the granules are fully saturated with PFAS molecules, they can 'regenerate'. This removes the PFAS molecules, so that the granules are ready for another round of decontamination. The successfully separated PFAS must then be stored or destroyed.

Finding peptide mimics that interact in the right way with both the granules and the pollutants has been no easy task. The team has generated enormous data sets with tens of thousands of data points to measure how well different materials stick to PFAS molecules of interest. They have patented one material that sticks to six of the most common PFAS.

Puraffinity has recently manufactured the granules at its largest scale yet, a batch of up to 50 kilograms. It is working with the German government to validate the product's safety at TZW, a site run by DVGW, the German Technical and Scientific Association for Gas and Water. "It has been third-party validated at the German government-owned site, and their sites in the US – so we can roll that out for industrial installations."

In this pilot phase, the team anticipates being able to treat 25 tonnes of water a day. Beyond the pilot, Puraffinity would be able to roll out to high-flow installations, treating up to 500 cubic metres (approximately 500 tonnes) of water an hour, equivalent to a typical chemical manufacturing plant's water use. Most of their sites are in the US or Europe, with more to be announced as they go live. "We want to keep the public onboard. Solutions are coming – it's not just that we're finding more [and more] PFAS!"

DESTROYING LEFTOVER PFAS

The final piece of the puzzle is what to do with the PFAS left after processing. In the past, researchers heated the waste to temperatures of up to 1400°C. However, this energy-intensive process can still release harmful chemicals.

As a result, many startups and researchers are searching for safer options. In October 2023, *MIT Technology Review* reported on several US-based PFAS destruction technologies, some established, others emerging. The Michigan-based company Revive Environmental uses an approach called supercritical water oxidation. Here, relatively high temperatures and pressures turn water to a supercritical state, where it has both liquid-like and gas-like properties. These conditions help to break the strong carbon–fluorine bonds, with inert salts its only byproducts. Other methods bombard PFAS with high-energy electrons, or use high pressures and temperatures coupled with alkaline catalysts.

According to Hagemann, the new destruction technologies are "exciting, but not [at a] commercial stage yet." He adds that these next-generation destruction companies also need "next-gen capture steps", such as Puraffinity.

Another destruction technology has emerged from Northwestern University in the US. The Northwestern team's August 2022 study in *Science* showed PFAS can be destroyed at temperatures of up to 120°C in a solution of two relatively harmless chemicals: sodium hydroxide or lye, a chemical used to make soap, and dimethyl sulfoxide. Only safe byproducts were left at the end.

More innovations in remediation are coming, and one promising approach is with ultrasound. Dr Madeleine Bussemaker, a chemical engineer at the University of Surrey, has been studying how to turn forever chemicals into relatively harmless carbon dioxide

PFAS have been widely used in waterproof clothing and outdoors equipment (such as ski wax) © Shutterstock

and fluoride. She and her colleagues reported in 2020 that ultrasound can completely degrade all PFAS so far tested. Although ultrasonic degradation is still at an early stage, the team aspires to develop a large reactor capable of treating contaminated domestic water supplies or firefighting foams and adapting the process for soils.

CHALLENGES REMAIN

While Hagemann describes existing technology to be "incapable of removing PFAS contaminants to the level required to keep up with these changing regulations", he agrees regulation is the way forward.

Although there have been proposals to ban PFAS (in March 2023, the EU began a public consultation on this – now abandoned), Hagemann does not support a total ban. "I'm a biomedical engineer and I know a double-digit percentage of medical devices, say, are manufactured using PFAS. How are you going to phase them all out as a class?"

Yet, he has been contacted by people who have had stents inserted in the heart because of built-up cholesterol, and checks have found them to have very elevated PFAS levels. "It's a sense of urgency that really centres us as a company. This is a once-in-a-generation chance for an engineer to have a real impact on people's lives," says Hagemann. He describes one way to lower the concentration of PFAS in your body: donating blood. A public study found that by giving blood, you donate a disproportionate amount of your PFAS.

Hagemann adds: "This space is one of the hardest problems being worked on in sustainable materials. You have the vast chemical design space, where brute force manual search isn't enough; and you have the nonlinear behaviour of PFAS, which requires you to have a lab and run the analytics to get the different disciplines speaking. It's not just money – it's also time. But the more focus we put on PFAS, the more companies will be trying to develop new alternatives."

They already are. In October 2022, the highest-profile brand in the outerwear materials industry, Gore-Tex, replaced its world-famous formula for waterproof clothing with its new PFAS-free membrane, GORE-TEX® ePE (expanded polyethylene) membrane. Patagonia, a leading role model in sustainable clothing, calls ePE "the game changer".

More recently, global chemicals manufacturer 3M pledged to discontinue its PFAS manufacture by 2025. In August 2023, the company reached a $10.3 billion settlement with the US government after claims by public water providers that it polluted drinking water with PFAS.

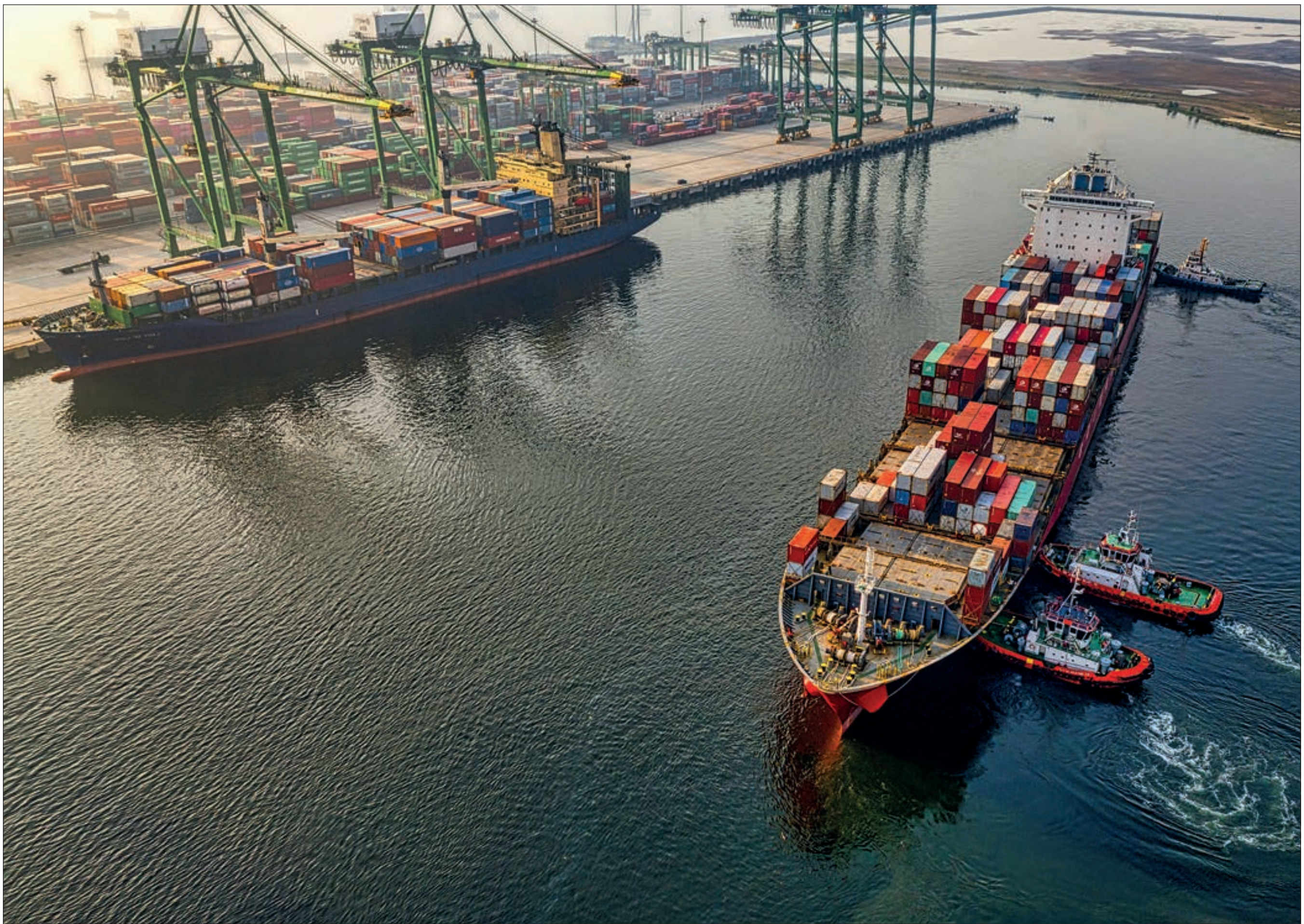
It just goes to show – alongside all the concern and challenges, there is optimism in the search for safe, clean solutions to remediating PFAS.

BIOGRAPHIES

Matthew Ingram is a chartered engineer who has worked with Cornelsen in the remediation industry since 2005. Over the past six years, his focus has been on treating 'difficult' waters, which include PFAS. This includes new and evolving technologies and sustainable options wherever possible.

Henrik Hagemann is CEO and Co-Founder of Puraffinity. He holds a master's in biomedical engineering from Imperial College London, specialising in advanced biomaterials and synthetic biology. Henrik is a Royal Academy of Engineering Enterprise Fellow, has trained in martial arts with the Shaolin Monks and cycled along the Silk Route, including China, Kazakhstan, Russia and Ukraine, in 87 days.

DECARBONISING THE SHIPPING INDUSTRY



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About 90% of traded goods are transported on the world's oceans, with total trade volumes likely to triple by 2050. However, shipping is currently reliant on fossil fuels, and widely considered one of the hardest-to-decarbonise sectors. So how will we do it? Leonie Mercedes explores the different possibilities for a green future for the industry.

Did you know?

- It's estimated there are between 50,000 and 60,000 cargo ships worldwide
- More than 500 ships pass through the English Channel each day, travelling from the North Sea to the Atlantic Ocean and vice versa
- The world's biggest container ships are longer than 33 double decker buses lined up end-to-end (too long to travel down the Panama Canal without getting stuck in its lock chambers)

Shipping lets us enjoy cotton from India, gadgets from South Korea and coffee from Brazil before we even leave the house each morning. The hundreds of components that make up your phone come from all over the world, meaning it's clocked up thousands of miles on the open seas before you ever switch it on. Shipping makes modern life as we know it possible – not to mention a lot more convenient and comfortable.

It's one of the least polluting means of transporting goods, as compared with air and road freight. Nevertheless, most of the world's fleet burns fossil fuels. So, it is still a significant source of greenhouse gas emissions, responsible for about 3% of the world's total. The ships that deliver goods to us also emit other pollutants, such as sulphur dioxide, that are harmful to human health and the environment.

Under the Paris Agreement, the International Maritime Organisation (IMO), the United Nations' regulatory body for shipping, has called for a 50% reduction in the industry's greenhouse gas emissions by 2050. To reach this target, engineers are working to make every part of shipping greener.

A sizeable component of these efforts, and yet just one part of the decarbonisation puzzle, is ship propulsion. To reduce emissions while keeping the world's ships moving, we need to decrease the amount of fuel we're using, replace it with something that produces less or no carbon, or both.

ALL ABOARD: SIZING UP THE CHALLENGE

Diesel engines still power the vast majority of shipping vessels today. They run on fossil fuels – typically heavy fuel oil, light fuel oil, or marine diesel oil. These are energy-dense fuels, so a little goes a long way. Although the efficiency of diesel engines has improved in the past half-century, and applying speed limits on ships can reduce emissions, more must be done to reach the IMO's target. As such, many companies are considering alternative fuels, including liquefied natural gas (LNG), biofuels and emerging options such as ammonia, hydrogen and green methanol.

However, the transition to a low-carbon future in shipping will be challenging. Fossil fuels are relatively cheap, the industry as a whole already operates on fine margins, and being a global industry, there are many moving parts to consider. Just one example: ships must be able to refuel on their routes, so the bunkering (fuel supply) facilities that are available internationally will drive fleet operators' decisions. To avoid disruption, change must be well-considered and gradual.

"What we're trying to do is replace a very cheap and a very effective energy carrier, which is a hard act to follow. And we have to do it at scale – enormous scale – and it has to be distributed across the UK and across the world," says Tony Roskilly, chair of energy systems at Durham University's department of engineering. "The scale-up is one of the biggest challenges."

Roskilly heads the UK National Clean Maritime Research Hub. Established in September 2023, the UK-MaRes Hub's goal is to accelerate decarbonisation in shipping and eliminate air pollution produced by marine activity, both at sea and at ports. It brings together 13 British universities as well as dozens of organisations from around the world, including shipping companies and fuel producers.

The UK shipping industry cannot be disentangled from international shipping, says Roskilly. "It's an international activity that drives the whole economy."

One of UK-MaRes Hub's objectives is to research sustainable marine fuels and their safe use. These proposed alternative low- or zero-carbon fuels include hydrogen, ammonia and LNG (see 'Sustainably transporting gas', *Ingenia* 84).

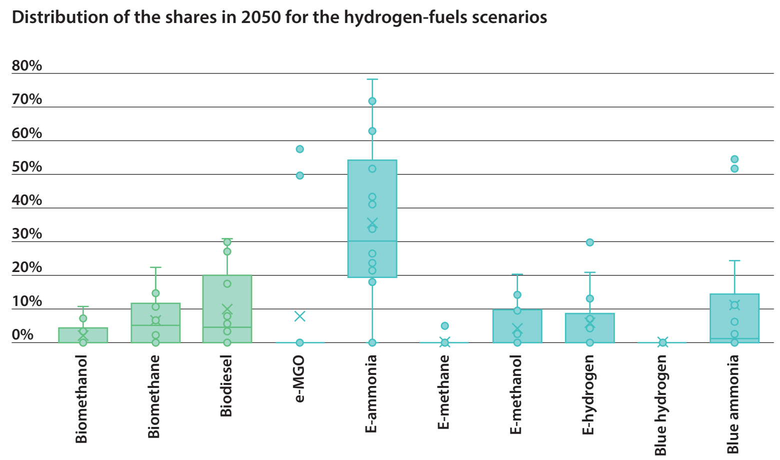
However, with any of the fuel alternatives, it is crucial to ensure that we're not reducing emissions from propulsion while increasing emissions elsewhere. This is important to consider in the whole lifecycle of any of the options. It includes production of the fuels themselves and extraction of any raw materials used, as well as the machinery required to store, transport and use the fuels.

FRONTRUNNER FUTURE FUELS

Hydrogen and fuels derived from it hold promise for zero-carbon propulsion.

Hydrogen can be mixed with other fuel sources and burned in combustion engines. It can also power fuel cells – an almost 200-year-old invention that enjoyed a resurgence during the space age, playing a role in taking astronauts to the Moon. Fuel cells combine hydrogen and oxygen to produce electrical and thermal energy, with both propelling the ship. The only exhaust is water. High-temperature fuel cells can be just as or even more efficient than diesel engines if the heat they put out is also used.

Although hydrogen produces no CO_2 or sulphur oxide when used in an internal combustion engine or fuel cell, current methods for producing it at scale are not carbon-free (see 'Making hydrogen and other fuels'). Furthermore, the infrastructure for



There are many different forecasts of the fuel mix for 2050, but many expect ammonia derived from hydrogen (e-ammonia) to be the most popular. While not discussed in detail in this article, biofuels are also expected to have a significant share. However, the maritime sector will be competing for this supply with the aviation industry. Adapted from The future of maritime fuels: What you need to know © adapted from Lloyd's Register Maritime Decarbonisation Hub, 2023

MAKING HYDROGEN AND OTHER FUELS

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The most common way to produce hydrogen is currently the steam methane reforming (SMR) process. In SMR, steam and methane are reacted to separate out the hydrogen, which creates carbon dioxide as a side product (as well as trace amounts of carbon monoxide).

To make the process carbon-free, chemical companies can capture the carbon as it is being made (in which case, the resulting gas is called blue hydrogen).

Alternatively, they can do away with SMR completely and produce hydrogen using water electrolysis (green hydrogen). Companies such as Ceres Power are developing electrolysers to do exactly this, which also work as fuel cells (see 'The clean energy pioneers', *Ingenia* 96). Green hydrogen can then be used to make (green) ammonia and methanol – themselves promising shipping fuels.

"It's not going to be a single golden bullet that solves the problem. It's going to be a combination of lot of different technologies coming together."

hydrogen, including storage and transportation, doesn't yet exist.

There are a few tricky challenges to address. For example, hydrogen is less energy-dense than conventional marine fuels – so you need a lot of it on board, at the expense of space for precious cargo. It's also highly flammable, introducing the need for more safety measures. Finally, it must be stored at high pressures or low temperatures, and storage systems that do this are likely to be heavy, making vessels less fuel efficient. As a result, some analysts think it's best off powering short-distance vessels.

This may make a purely hydrogen propulsion method unviable for the time being, but engines that work with more than one fuel could help bridge the gap. Along with his team, Roskilly has been developing a combined system that can be fuel-flexible, meaning it can work with fuels other than hydrogen: "We've done a lot of work on hydrogen," Roskilly says, "but there are other hydrogen carriers [substances that can store and transport hydrogen] that are of interest, particularly for the marine sector and other industry, such as ammonia, methanol, and a lot of other alternatives."

This provides flexibility, as the fuel that will ultimately emerge dominant across the sector is still a big unknown. "The technology that we've developed has the advantage of being able to adapt to a new fuel source, so that when we're going through this transition, we're not reliant on hydrogen."

Ammonia (NH_3) is another alternative fuel being considered. Many consider it likely to become the long-term solution, as it is much easier to store and more energy dense than hydrogen. It can be burned in diesel engines and gas turbines, and although it produces no CO_2 on board, current methods for its production, which involve SMR and the Haber process, are not carbon-free. If it is to solve the decarbonisation problem, it will need to be made 'green' from green hydrogen. Sustainable energy startup Amogy is exploring how ammonia made from green hydrogen can be harnessed in zero-carbon shipping.

Green methanol is another fuel that can be derived from green hydrogen. In September 2023, Maersk announced a startup, C2X, which aims to produce 3 million tonnes of green methanol per year by 2030.

As a fuel, LNG generally produces about 25% less carbon emissions than conventional fuels, and no sulphur oxides. Many companies have been adopting LNG, which can be used with the fuel systems currently in use.

However, the main component of LNG is methane, itself a greenhouse gas 21 times more potent than carbon dioxide, and so it must be handled with care. Methane slip – where the gas escapes into the atmosphere during refuelling or through engine systems – may override any benefits of using the less carbon-heavy LNG as compared with heavy fuel oil. Companies including Wärtsilä and MAN Energy Solutions are working on engines aimed at reducing methane slip.

A GREEN FUTURE FOR SHIPPING?

Developing alternative fuels and greener methods of propulsion is just one element of decarbonising the shipping industry. The entire lifecycle must be considered to secure a sustainable future for the sector.

As an industry, shipping covers a range of activities, encompassing everything from ferries that go back and forth across relatively short distances, to large container ships that go on weeks-long voyages across oceans. No one solution can apply to all of these activities. "The solutions will be different for different sorts of vessels and different classes of vessels," says Simon Schofield, Chief Technology Officer at BAR Technologies, which has developed the WindWing to harness wind in ship propulsion (see 'The return of wind').

"It's not going to be a single golden bullet that solves the problem. It's going to be a combination of lot of different technologies coming together."

The complexity of the challenge demands expertise from a wide range of disciplines, so it's important that engineers, academics, and those in industry work together. Indeed, this was the thinking behind UK-MaRes Hub.

"It's crucial that we bring all of the skills and disciplines together to work on this complex system," says Roskilly. "In the vast majority of research programmes that I'm working on, we incorporate colleagues from geography, anthropology, business... all different disciplines."

The transition to net zero will take time – diesel engines dominate the shipping industry and have done for decades. It's a well-established technology where repairs and spare parts are relatively easy to come by, and that engineers the world over understand. For many of the potential future fuels, the infrastructure needs to change before wider adoption, from engines to storage. That won't happen overnight.

"We have to think of this as a transition," says Roskilly. "We're talking about global shipping, thousands and thousands of ships moving and delivering 80 plus percent of everything we eat, touch, wear."

However, at least one recent development has shown that change is possible. Use of heavy fuel oil fell dramatically after the IMO imposed a limit on sulphur content in fuel oil. Many shipping companies based in the Nordics aim to become carbon neutral by 2050, which would surpass the IMO's deadline. This implies that if conditions are right, and there is the will and the means, transformation in the sector can happen. A comforting thought when after a long day, having returned home on the bus (from Germany), you lay your head down on your pillow (from Sweden), and turn off the light (from China).

THE RETURN OF WIND

The Berge Olympus has four WindWings, saving 6 tonnes of fuel per day
© BAR Technologies

The shipping industry is also looking at renewable sources of energy, such as wind. When used in combination with fuel propulsion, wind can reduce the amount of fuel needed and so take a good bite out of the greenhouse gas emissions it produces.

Towards this goal, marine engineering firm BAR Technologies has created the WindWing, born out of knowledge developed racing yachts at the America's Cup, the 'Formula One of the Sea'.

WindWings produce thrust in the same way wings produce lift for an aircraft. Each wing has three separate elements so that its shape can change, making it possible to control the amount of thrust produced. They are made primarily of steel, with an outer surface of fibre-reinforced plastic. They're made in the same way as wind turbine blades and built in a wind turbine factory.

WindWings set sail on its maiden voyage atop a Cargill vessel last summer. BAR Technologies had previously worked with the company, which operates a fleet of about 650 vessels and in 2021 moved more than 200 million tonnes of cargo, to improve its fleet's efficiency.

Depending on wind speed and direction, each WindWing is estimated to reduce fuel consumption by 1.5 tonnes per day. So, while modern wind power systems can provide some assistance to fuel propulsion, fully powering a ship is out of the question for now.

BIOGRAPHIES

Tony Roskilly is Professor of Energy Systems at Durham University and the Director of the UK National Clean Maritime Research Hub. He is a Fellow of the Institute of Marine Engineering, Science and Technology and a member of the Department of Transport College of Experts.

Simon Schofield is the Chief Technology Officer of BAR Technologies. His 20 years of wide-ranging experience in technical development of grand prix racing yachts includes multiple Americas Cups Campaigns, Volvo Ocean Races, and Offshore and Inshore Grand Prix Race yachts.

HORIBA MIRA's 'highway' facility has a fully configurable dynamic platform with an approach 15 lanes wide. It's used for testing a range of scenarios involving advanced driver assistance systems and connected and autonomous vehicles, such as lane merging, lane assist, platooning, and autonomous emergency braking © HORIBA MIRA

CAR TESTS ON A DIGITAL TRACK

Automotive engineering requires an increasingly complex combination of physical testing and digital simulation. Neil Cumins visited the UK's leading vehicle engineering and test consultancy to find out how tomorrow's vehicles are being put through their paces using digital twins, accelerated simulations and physical testing.

The automotive industry is a vital part of the UK economy. More than 25 manufacturers build over 70 vehicle models in the UK, supported by 2,500 component providers and some of the world's most skilled engineers. The rise in electrification and vehicles with advanced driver assistance and automated technologies, such as adaptive cruise control, autonomous obstacle avoidance and autonomous parking, is changing how automotive engineers develop and test new vehicles. A key player in the UK's support system for car makers is HORIBA MIRA in Nuneaton. With a team of more than 500 staff, HORIBA MIRA, one of many automotive businesses on the MIRA Technology Park, maintains test equipment and road facilities that can subject vehicles – human-

Did you know?

- Automotive-related manufacturing contributes £67 billion turnover and £14 billion value added to the UK economy, and manufacturers typically invest about £3 billion each year in R&D
- In 2022, over 775,014 cars, 101,600 commercial vehicles and 1.5 million engines were built in the UK, and 8 out of 10 cars produced in the UK are exported overseas to 130 different markets worldwide
- More than 1.6 million new cars are sold in the UK each year

driven and autonomous, electric and combustion, civilian and military – to physical and virtual testing. Vehicle makers and their suppliers use this independent engineering and test consultancy to improve everything from durability to levels of autonomy on 'self-driving' cars.

The site is home to the MIRA Technology Park, a mobility technology cluster focused on automotive R&D. With more than 35 major companies on the site including Polestar, REE Automotive, ClearMotion, and Bosch, the technology park claims to be 'Europe's largest automotive R&D cluster'. As an ecosystem for the development of automotive technology, many tenant companies also use HORIBA MIRA's vehicle development facilities co-located onsite.

RECREATING REAL ROAD CONDITIONS

A key component of automotive engineering is the ability to test new ideas in a real-world environment. To enable this important element of R&D, HORIBA MIRA opened a £100 million ASSURED CAV test ecosystem in 2022, for the engineering and testing of connected and autonomous vehicle (CAV) technologies. It contains an outdoor city circuit that recreates common features of built-up areas including traffic lanes, configurable junctions and a multistorey car park. The test circuit has wider use beyond the automotive industry: the telecommunications and electronics industries, as well as highways authorities, can carry out trials of intelligent transport systems (ITS) and telematics in a controlled environment. The city circuit is also a test bed for advanced driver assistance systems like radar-guided cruise control and self-parking technology.

"We've got a mini roundabout going onto a multi-lane roundabout, which is one of the most complex systems for autonomous vehicles to navigate," explains Alastair Evanson, HORIBA MIRA's Head of Strategic Sales for ASSURED CAV. "On-street parking bays let vehicles reverse out of spaces, testing rear automatic emergency braking. We also have traffic signal intersections and areas of the road network that are purposely degraded." This is to replicate the various conditions of public highways. The site also has a network of banked circuits, rough roads and dry/wet weather proving grounds, where clients can test key factors such as vehicle dynamics.

The deliberately worn-down or varying line markings on road surfaces are designed to create a safe, controlled environment that will challenge driver assistance systems. By using these facilities, vehicle manufacturers can identify how small variations in road layout and markings may have a disproportionate impact on the effectiveness of the system under test. For example, a vehicle using features such as lane-keep assistance could successfully navigate a corner in one direction; however, in the opposite direction at the same speed but with impaired road markings, it may fail to maintain its performance. One small variation can impact a test's outcome, showing there is still work to be done before manufacturers can deploy fully autonomous systems on a widespread scale.

Urban and suburban driving environments can be recreated to validate complex automated driving systems under safe and repeatable test conditions
© HORIBA MIRA

"Automation and associated testing are complex issues that the industry is working on collaboratively to fully understand," Evanson explains. "The government is developing national safety principles that stipulate a system needs to follow the highway code and operate at least as well as a safe and competent driver. These guidelines are being worked on jointly with industry to ensure appropriate robustness and applicability."

HORIBA MIRA works with clients to evaluate the robustness of their system to meet regulatory requirements but also meet consumer expectations of performance. "They want the system to work, for example, in certain weather conditions with specified road markings up to 96 kilometres per hour with a given turn radius," says Evanson. "We'll work out a test plan that will encounter the variations you could get within that design, and then identify how to build statistical confidence around the performance of the system with those variables."

HOW TO PARK A CAR

Safety has always been an important part of the work at the site. The nature of that activity has changed over time, driven most recently by the development of CAVs and growing consumer reliance on systems that automate vehicle movements.
To support the development of technologies for self-parking vehicles, the city circuit incorporates a new multistorey car park with a variety of ramp styles, space markings and light levels that can replicate real-world designs. It is also equipped with power, Wi-Fi and configurable lighting. Two floors have the same footprint with one in the open-air, so that customers can see how a vehicle's camera system operates in the light versus the dark.

HORIBA MIRA also developed an indoor localisation system for automated valet parking. This compensates for the fact that signals from global navigation satellite systems (GNSS) cannot penetrate steel structures. The local network provides GNSS accuracy down to one centimetre so that clients can test their vehicles' self-parking abilities in various environments.

ASSURED CAV parking replicates the challenges of real-world situations to help develop self-parking solutions, allowing representations of vulnerable road users to be incorporated into test scenarios © HORIBA MIRA

It has also adapted the wider test facilities at Nuneaton to keep up with the move toward CAVs. Along with the car park's indoor localisation system, the wider ASSURED CAV area has a 5G network so that clients can test communications with vehicles, without data being visible beyond the site's boundaries. This avoids external interference and ensures reliability.

VIRTUAL AND SIMULATED ENVIRONMENTS

The growing use of computer modelling and simulation in engineering has given rise to the development of 'digital twins', computerised replicas of the new technologies that engineers plan to develop (see *Creating a virtual replica*, *Ingenia* 87). HORIBA MIRA's engineers have created digital twins of every road surface, so that road tests can compare real-world results with digital simulations.

HORIBA MIRA's work is split roughly equally between testing and engineering programmes – testing performance against specific target requirements or providing consultation and guidance to support customer R&D. The balance has slowly shifted towards the latter with the evolution of virtual technology. Digital twins and computer modelling have reduced the amount of physical testing required. A key benefit of using simulators and test rigs instead of test vehicles and prototypes is decarbonisation. Replacing a physical prototype with a virtual one slashes emissions, tyre usage and component consumption. Onsite test facilities can stress test components without clocking up unnecessary mileage.

Its newest virtual facility is its Driving Simulator Centre, which incorporates both dynamic and static driver-in-the-loop (DiL) simulators with the support of HORIBA MIRA's engineering expertise. The centre can help reduce the time it takes to develop a new vehicle. The dynamic simulator moves a test vehicle around on a fixed base plate with images on a wraparound screen corresponding to the simulator's movements. The software powering this setup takes feedback from a vehicle mounted on the hexapod robotic base. Known as a buck, this is typically a production vehicle with both ends removed.

Alongside collecting data, the vehicle's largely intact cabin has a driver sitting inside the vehicle to subjectively test the key attributes of any vehicle, noise, vibration, and harshness along with steering, suspension and throttle responses. Eye-tracking software can determine how much drivers take their eyes off the road to look at the dashboard, which can help reposition the vehicle's displays to improve safety.

As well as cutting carbon emissions, simulators can slash development times and costs. "If you think about a traditional development programme being three or four years," says Jonathan Maybin, Head of Sales for Vehicle Attributes and Performance at HORIBA MIRA, "you wouldn't be able to drive a representative physical vehicle until 15 to 20 months into that programme. You've then got a small window to do validation, tuning and development work." The simulator can produce data even before there is a vehicle design so that the simulation team can work on the suspension architecture.

Maybin cites active systems such as rear-wheel steering, which depend on producing software as well as hardware. "It is very challenging to do the amount of software tuning needed purely in the physical world with the complexity of active systems. You still need physical tuning and validation, but you can get a long way there in the virtual phase. If you can do the calibration six months into the development programme, instead of two years into a physical test, that dramatically accelerates the process."

An engineer tests a vehicle in the driving simulator © HORIBA MIRA

The simulator is used in parallel with real-world testing on the proving ground outside the building. "We find OEMs [original equipment manufacturers] are still using it during physical validation," says Maybin. "If there's bad weather or you're wanting to make a significant change to the physical vehicle, you don't want to pull a vehicle off the track for a day to make that change, you can make a decision in the simulator regarding the development direction before committing to that change on the physical vehicle, enabling a more efficient physical validation phase."

With this introduction of digital twins and the driving simulator, Maybin sees HORIBA MIRA's future as "doing more and more work virtually."

PERFECTING THE PROTOTYPES

REE Automotive is an example of how manufacturing clients can combine HORIBA MIRA's physical and virtual testing with their own engineering activities. REE Automotive, a startup business with an innovative approach to the design of electric vehicles, set up its own engineering centre on the MIRA Technology Park. The company's architecture puts the traditional drive components – steering, braking, suspension, powertrain, and control – into the arch of each wheel.

Peter Vow, Vice President of Engineering at REE, explains that his role is to take the technology and ideas that have been generated and bring them into full-blown production. "Everyone can make a one-off, but can you make thousands of them?" To answer that question, REE tapped into HORIBA MIRA's expertise.

"We relied heavily on HORIBA MIRA at the start to supplement our engineering team," he explains. "It takes time to recruit and bring talent in. We could supplement that with the HORIBA MIRA team while we built our team in parallel."

Using the driving simulator and modelling software has saved REE a considerable amount of money on prototypes, says Vow. "We've built very few vehicles, because they cost a lot of money. I think you can get 80% of the way there digitally, but there'll always be elements you've got to do practical testing on."

That's the point where prototypes are introduced to HORIBA MIRA's outdoor test facilities. REE also intends to test models for the overseas market at HORIBA MIRA, using facilities like US-standard driveways and Indian speed humps.

BIOGRAPHIES

Alastair Evanson is HORIBA MIRA's Head of Strategic Sales for ASSURED CAV. A degree in city and regional Planning led mountain-biker Alastair to transport and mobility planning roles in Qatar and the UAE. This was followed by a stint working in Germany for a simulation software provider. After returning to the UK, he joined HORIBA MIRA, where he supports customers in the validation and verification of automated and connected technologies.

Jonathan Maybin is Head of Sales for Vehicle Attributes and Performance at HORIBA MIRA. Jonathan has a BSc in motorsport engineering, with his passion for motorsport leading him to compete in a variety of motorsport categories across the globe. He has spent time in the mining industry as a technology support engineer before returning to the automotive industry, joining HORIBA MIRA in 2015. He now leads the commercial team focused on automotive attribute engineering services across multiple vehicle segments.

A CHAMPION OF THE GREEN ECONOMY

Professor Simon Pollard OBE FREng's confidence in the idea of a circular economy began when he set out to turn harmful waste into useful materials. His career as an environmental engineer has encompassed many aspects of the waste and water utility sectors, including pioneering risk analysis in the management and regulation of public health infrastructure systems.

Professor Simon Pollard OBE FREng remembers being impressed by the 1972 report *The Limits To Growth*. This seminal analysis on the use of resources was an early advocate of the role of recycling in economic growth. The idea that we should make better use of resources influenced his choice of a career as an environmental engineer. For a while, Professor Pollard was one of a small community of engineers who saw the circular economy as essential for the survival of the planet and those of us who live on it. Today, sustainability has permeated economic activities far beyond the world of engineering.

Professor Pollard's path into environmental engineering began as an early school leaver. His chemistry teacher was "an entertaining practitioner who delighted in trying out experiments in front of the class", but that wasn't enough to keep him motivated. He was, he says, restless at school and left at the age of 16 after responding to a job ad read out in class, which eventually led to a role as a technician working on thermoplastics for Raychem in Swindon. Professor Pollard says he learned a lot in the two years spent developing novel materials for the booming digital telecoms sector.

Professor Pollard describes the company as a "superb, 'Silicon Valley-style' crucible of innovation, led by charismatic entrepreneurial technologists". The patent-hungry approach to R&D, where collaboration was what mattered, left an impression on Professor Pollard. As well as bench experience that was to prove invaluable, Raychem also gave him time to study for a Higher National Certificate in physical sciences, along with a company scholarship to go to university. Thanks to a "a kindly admissions tutor willing to take a punt on a vocationally educated lad", as he puts it, Professor Pollard returned to education as a chemistry undergraduate at Imperial College London, where his practical experience in the lab compensated for his lesser appetite for organic synthesis.

On graduating, Professor Pollard wanted to move back into technology. The rise of environmental engineering in academic circles had prompted Imperial to create the Department of Civil and Environmental Engineering, with Professor Roger Perry, Head of Environmental and Water Resource Engineering.

Professor Pollard was keen "to do something practical". Perry offered Professor Pollard an industrial studentship working with Laporte Industries, the multinational chemicals group, in the emergent field of hazardous waste management. Thus began Professor Pollard's move into environmental protection and sustainability.

TACKLING WASTE

Industry came under increasing pressure in the 1990s to clean up its act, literally. Professor Pollard's PhD tackled "particularly problematic industrial waste". The process used to bleach edible oil created waste that had a habit of spontaneously igniting when dumped into landfill. In his PhD project, Professor Pollard used chemical principles in an engineering setting to develop a patented process that converted the waste into a usable product.

For Professor Pollard this was an early foray into the circular economy and more research into turning waste into useful materials: "It was in the era of waste minimisation. Companies were looking afresh at all their industrial wastes and seeing how they could be minimised, and in some cases reused."

Thirty years ago, these concepts had yet to become a natural component of industrial thinking. A lot has changed since then. Professor Pollard's own thinking developed when a postdoctoral research opportunity came up in Canada. Professor Steve Hrudey, one of Perry's former students, ran the environmental health programme at the University of Alberta. He was supporting Alberta's clean-up of contaminated land in the province's former railway yards and wood preserving sites.

The challenge was to devise the most effective ways to reduce the risks to health and the environment. "Working with Steve gave me a superb foundation into the preventative management of risk," says Professor Pollard. Risk management entails assessing risks and, where necessary, intervening before impacts cause harm to public health or the environment.

Professor Pollard began to implant this thinking on his return to the UK. In 1994, after a short period teaching environmental chemistry at the University of Edinburgh, he put his academic career on hold. He drew on his experience working in contaminated land by joining a consulting business that had won the contract to clean-up the former Ravenscraig steelworks, south of Glasgow, which had ceased steel-making in 1992. This was a massive remediation project, and as he puts it, a "formative two years" learning about sales, client care and corporate risk.

RISK ANALYSIS AND POLICYMAKING

Reflecting on his career, Professor Pollard identifies times when it felt more of a 'random walk' and others when his journey was more purposeful. In 1996 that journey took him into the public sector with an invitation to join the newly formed Scottish Environment Protection Agency. Two years later he moved on to the national stage and to Westminster to run the national risk analysis team at the Environment Agency (EA), then just two years old.

These were early days not just for the EA but also for new thinking in environmental policymaking. Policing the country's water system, from supply through to flood management, was one of the organisation's main tasks. "This was a career opportunity to form a team of risk analysts from scratch," says Professor Pollard. This was happening at the same time as the EA was grappling with BSE and foot and mouth crises, major flooding events, and contaminated land, while also working on regulation of hazardous and radioactive waste.

Professor Pollard's new challenge demanded a subtle blend of engineering expertise and political skills. The task involved developing technical and regulatory tools and approaches to support large national-scale projects where environmental and engineering risks were at the fore. It was also an invitation to contribute to new thinking on public risk management, "all at a time when successive governments were dealing with the deregulation agenda, cost-sharing for the management of public risk, and the design of risk-based regulation".

QUICK Q&A

What inspired you to become an engineer?
In my PhD years, the prospect of applying engineering know-how to public health and environmental protection.

Favourite project you worked on?
Hugely challenging, but working with government on characterising the environmental impacts of the foot and mouth and BSE crises in the 1990s.

What's your advice to budding engineers?
Keep developing your skills, and network outside your own discipline to understand the perspectives of others.

Best bit of the job now?
Witnessing the passion that today's young engineers have for making the world a better place.

Do you have a favourite tech gadget?
I cherish a fabulous modern corkscrew that is a delight to use.

Most impressive bit of engineering to look at?
The delightful Forth Bridge, Edinburgh.

What do you do in your spare time?
I enjoy the landscape of north Norfolk and the food of Southern Italy.

The influential and best-selling report *The Limits to Growth* set Professor Simon Pollard on the road to sustainability and the circular economy as driving forces in his career in environmental engineering. As he sees it "the engineering profession has brought sustainability centre stage in a way in which other professions have sometimes struggled to do"

Professor Pollard says that five years at the EA gave him hugely valuable insights into the relationship between science and policy. The organisation's nature and remit meant working with practical, pragmatic people who could identify and get the evidence needed to inform regulatory decisions. "They had contractors, researchers and academics input to decisions, but they were extremely adept at making decisions around industrial sites, radioactive waste management, for example, and hazardous waste facilities, where national decisions were being made. I was very lucky to work there."

WASTE AND WATER MANAGEMENT

Professor Pollard enjoyed working at the EA but missed teaching, so in 2002 moved to Cranfield University as a research professor. He subsequently became Head of Department and, in 2014, Pro-Vice-Chancellor of the School of Water, Energy and Environment, which represented a summation of Cranfield's sustainability expertise. The university had long been active in engineering aspects of water supply and management (see 'Water research'). A series of research contracts for the US Water Research Foundation followed that drew heavily on Professor Pollard's experience in risk, regulation and public health protection.

As Professor Pollard sees it, the UK is well placed to play a role in this important international sector. "We've got a vibrant water research community." With universities such as Cranfield, the UK is also training the next generation of process and environmental engineers. Professor Pollard has also worked with senior engineers in the water sector beyond the UK, including Canada, Australia, the US, and Portugal.

"Research councils have always supported water and wastewater engineering. Also, I think, the foresight to understand that it's not just about the systems and the engineered systems, but management and people capability also play a large part in all of this."

On joining Cranfield, Professor Pollard also started what has become an influential programme of research on environmental risk. The Department for Environment, Food and Rural Affairs (DEFRA) wanted to compare risks across its broad portfolio of responsibilities, whether it was veterinary issues, air pollution, pesticides in the environment, or radioactive waste. As part of this work, the research councils and DEFRA put out a call for risk expertise. "They established a collaborative programme with the research councils and called for a national risk champion." Professor Pollard explains. "I was lucky enough to win that."

Given the multidimensional nature of risk, and range of perspectives that people have, explaining risk management can be a challenge. Reflecting over years of experience, Professor Pollard's preference is to start simple and build in complexity, only as it adds value to the decision on how to manage risk. "For environmental risks, one has a source of a hazard with the potential to cause harm to something we value, and a pathway of exposure. There are opportunities to reduce hazards, but most of the intervention we do in engineering terms is in managing the exposure pathway to isolate the hazard from the asset that we value."

Since then, Professor Pollard has had a leading role in the implementation of risk-based regulation. This meant working with government and industry on, as he puts it, "the proportionate use of risk-based decision-making". As a part of this activity, Professor Pollard worked with DEFRA's then Chief Scientific Adviser, Professor Sir Robert Watson CMG FRS, taking forward some of the thinking on risk that he had started at the EA.

One target for this work was the water sector. "I became captivated by how the international water sector might improve its approach to risk and resilience. It needed to improve its governance of risk. That brought in not only the engineering side, but the policy and internal machinery that the sector has for governing risk across its portfolio."

When looking for reasons for the industry's current problems, Professor Pollard comes back to risk management. "You've got to know where the risks are. You've got to know how to manage your asset base with the investment that you choose or are allowed to put back in." He hints that some of the current criticism misses the mark. For example, combined sewer overflows may be blamed for releasing raw sewage into rivers, but they also protect the public from sewage backing up into houses. On the positive side, Pollard underlines the role of the European Water Framework Directive. "It's a shame to see the perception of that being undone. There's a job to be done to win back the trust of the public."

IN PURSUIT OF SUSTAINABILITY

The combination of engineering, environmental protection and risk analysis is relevant well beyond water, especially in an era when the world is grappling with climate change. There is a growing acceptance that engineering is crucial in the pursuit of sustainability.

With about 75 PhD and MSc researchers, Cranfield University is a leading centre for R&D in water engineering. It has attracted a steady flow of funds over many decades from research councils, government agencies and the water industry. With unique pilot-scale water and wastewater engineering laboratories, alongside the university's own sewage treatment works, researchers can evaluate engineering processes to be evaluated with authentic wastewaters © Cranfield University

Fortunately, engineers can turn to new tools as they address these challenges. While much of the world is getting worked up about the threat of artificial intelligence (AI) to humankind, Professor Pollard is keen to explore the possible benefits. "One of the challenges of environmental risk assessment is the sheer number of exposure pathways between hazardous agents and the people, assets and ecosystems that we seek to protect from harm," he explains. "Artificial intelligence offers the potential to analyse these interactions and their supporting evidence at far greater speed and clarity than we can currently."

The world has caught up with that earlier analysis of the state of the planet that set Professor Pollard on the road to sustainability. *The Limits to Growth*, he says, was "a superb piece of work." It may have taken time, but he sees signs of hope in new thinking about economics and resource management and the overwhelming rise of scientific evidence on climate change. "We've gone past a period of scientific uncertainty." Even business has seen the point. "None of this is overnight, but the transitions are underway. There's phenomenal support, I think, within the business community, but we can't just slip back into short termism."

WATER RESEARCH

Water utilities supply one of life's essentials. Their product has to be safe, wholesome and affordable. As Professor Pollard says, if things go wrong, utilities can't issue a product recall. To ensure that safety, Cranfield's research laid the foundations for the sector to adopt risk management as a formalised business process.

Research on all aspects of water systems run through Professor Pollard's career as an environmental engineer. He joined Cranfield University in 2002 and ran the School of Water, Energy and Environment for seven years. Cranfield even has its own sewage treatment facilities. "If you want to develop something at pilot scale, with the fundamental science and engineering behind it, then Cranfield is the place to do it."

The university's engineering expertise includes the Water Science Institute and the Centre for Water, Environment and Development. These combine research and postgraduate teaching in engineering, environmental risk analysis and governance, with about 50 PhDs and 25 MScs.

With its focus on graduate education, Professor Pollard points to the number of Cranfield alumni in the water industry. To bring these people together, the university created a risk manager network to enable collaboration between utility executives and regulators on risk.

The water industry is also fertile territory for Professor Pollard's interest in the circular economy. "A modern view of wastewater is as a resource, in terms of nitrogen and phosphorus, and the potential to produce gas," he explains. "Most water utilities have considerable energy bills, as you can imagine, and carbon footprints as a result. So they're interested in any opportunity to reduce carbon and improve renewables on site."

At a broader level, he adds, "We've looked at some of the various formats for producing hydrogen at scale."

For all the problems the world faces in moving towards a sustainable society, Professor Pollard is optimistic about the future and our ability to rise to that challenge "You have to be," he says with a laugh, before adding "and engineering, risk management and regulation are at the very heart of it."

CAREER TIMELINE AND DISTINCTIONS

Studied chemistry at Imperial College London, **1984**. Gained a PhD in environmental engineering at Imperial College London, **1990**. Senior consultant remediating the former Ravenscraig steelworks, Glasgow **1994–1996**. Policy adviser with the Scottish Environment Protection Agency, **1996–1998**. Head of Risk Analysis and Policy, Environment Agency, **1998–2002**. Joined Cranfield University as Professor and Director of the Integrated Waste Management Centre, **2002**. Fellow, International Water Association, **2012**. Pro-Vice-Chancellor, School of Water, Energy and Environment, Cranfield University, **2014–2021**. Fellow, Royal Academy of Engineering, **2017**. Pro-Vice-Chancellor International, Cranfield University, **2018–present day**. Appointed a Member of the Order of the British Empire, **2020**.

MAKING VITAL DIAGNOSTICS MORE ACCESSIBLE

With hysteroscopies, clinicians can explore the causes of infertility, repeated miscarriages and abnormal bleeding. However, delayed access to them in South Africa is causing patients unnecessary distress and health risks. With a new medical device, Cape Town-based startup FlexiGyn is working to make the procedure mobile, affordable and pain-free.

Co-Founder Edmund Wessels demonstrates the clinical setup with the FlexiGyn device and an anatomical model
© FlexiGyn/Brett Eloff

EYES ON THE INNOVATORS

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

Enfys, a new instrument that will search for life on Mars, will be built at Aberystwyth University

Initial tests have shown a new **Rolls-Royce** engine can run on sustainable aviation fuel

Hysteroscopies allow clinicians to see inside the uterus, using a tiny camera on the end of a long, thin tube. However, within South Africa's overburdened healthcare system, access to the procedure is limited. Patients may wait 6 to 10 months to be diagnosed and treated in hospitals because of the prohibitive cost of mobile hysteroscopy systems. Aside from severe emotional distress, this delayed care can mean that causes of infertility or cancer go undetected.

FlexiGyn's affordable mobile device aims to solve this problem. It features a slim, flexible scope tip with a patented bending mechanism to navigate the uterus without discomfort to patients.

MOBILE HYSTEROSCOPIES

Co-Founder and CTO Edmund Wessels first identified the need for a mobile hysteroscopy device during his biomedical engineering master's at the University of Cape Town. For the research component of his course, he was paired with a gynaecologist who highlighted the fact that hysteroscopy procedures were largely confined to operating theatres. "In South Africa, the tools to do [mobile hysteroscopies] are incredibly expensive and pretty much out of reach for gynaecologists, in both the public and the private sector," says Ed.

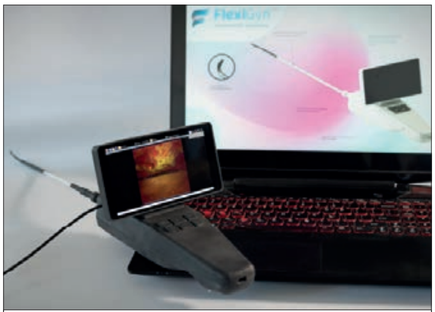
Convenience aside, early screening is vital. Among the causes of abnormal uterine bleeding are misplaced coils (intrauterine devices) and growths such as fibroids and polyps that can cause infertility. In rare cases, polyps can mutate and become cancerous – but are easily treated when caught early enough. "We can treat these in office in 10 minutes, instead of women having to wait 10 months," says Chris Meunier, FlexiGyn's other Co-Founder and CEO. Ed cites research showing that 60% of patients can avoid the operating theatre if abnormalities are caught early via hysteroscopy.

Another issue is the outdated tools often used. "Rigid straight scopes cause a lot of pain to patients, given that it's not a straight channel that they're working in," says Ed. "It needs tools like speculums and tanaculums [gynaecological tools used to aid cervix examination]. So even though it's a non-invasive procedure, it ends up being invasive to the patient."

A PAIN-FREE PROCEDURE

Thanks to FlexiGyn's patented bending mechanism, the tip of the scope can bend 130 degrees in either direction, for anatomies where the uterus is tipped slightly forward or backwards. "But the most important thing is obviously getting it down to a scale that can enter through the cervix without causing pain," says Ed.

Doing this involved not only a scaled-down bending mechanism, but also incorporating all the hardware, such as a camera and light source, into a tip less than 4 millimetres wide. A disposable sheath to keep the scope sterile (and therefore reusable) was itself highly engineered. It had to have multiple channels, one for the camera hardware, and another to fill the uterus with saline solution (key to observe the interior cavity).



The handheld unit is designed to be suitable for a mobile clinic and includes a built-in display © FlexiGyn/Brett Eloff

All of this is incorporated into a handheld unit, making the whole system suitable for a mobile clinic – including controls for navigating, taking videos and images, and a built-in display for the clinician to observe the procedure.

Trials with doctors (who have so far tested the device on anatomical models) have already garnered a lot of positive feedback. Now, the FlexiGyn team is finalising designs based on the user testing, closing a seed round of funding, and preparing for clinical trials. The goal is to have a beta product next year to pilot locally with nurses and gynaecologists before launch.

"We can't wait to have this in the hospital, in the clinic," says Ed. He talks of how, while pitching at the Africa Prize finals, women would open up to the team about their experiences and those of friends and sisters who were struggling to get treatment – and how excited they were to see innovation in the space. "It was really cool to get that in this journey – that we're working on something that people are excited for."

Edmund Wessels is a joint winner of the Africa Prize for Engineering Innovation 2023. His fellow joint winner is electrical engineer, Anatoli Kirigwajjo, who was selected for YUNGA, a community 'panic button' inspired by traditional African warning drums. Find out more about YUNGA at yunga-ug.com and in *Ingenia*'s next issue. Founded by the Royal Academy of Engineering, the prize is Africa's biggest dedicated to engineering innovation. It awards commercialisation support to African innovators developing scalable engineering solutions to local challenges.

Boston Dynamics' robotic dog **Spot** is cleaning up radioactive waste at the Sellafield nuclear site in Cumbria

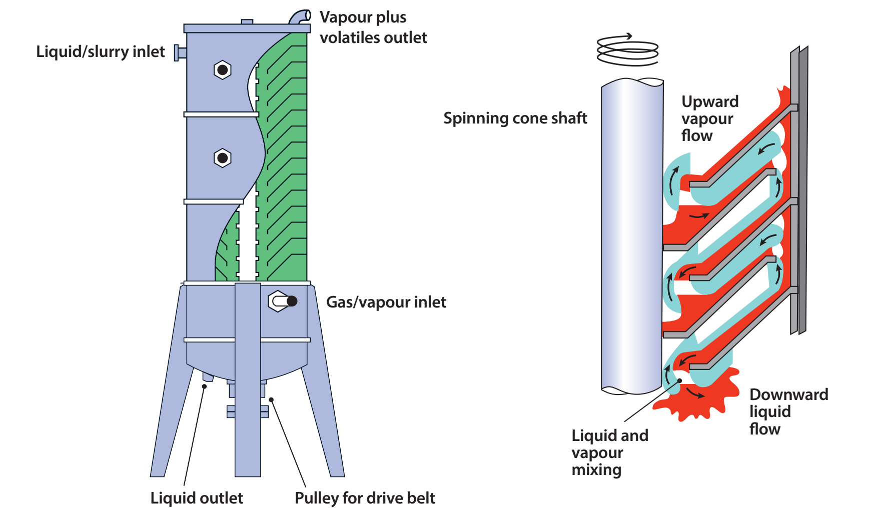
Notpla has been recognised as the first and only plastic-free packaging under EU's strict Single-Use Plastics Directive

Across the pond, startup **Heirloom** has launched its new carbon capture plant

HOW DOES THAT WORK?

NON-ALCOHOLIC BEER AND WINE

Sales of non-alcoholic and low-alcohol drinks have soared in recent years, more than doubling since before the pandemic. As we enter the festive season, we investigate how they are made to be alcohol free while still tasting the same.



Vacuum distillation takes place inside a stainless-steel column. Within this, the liquid is passed through a series of spinning cones to form a thin liquid from which the alcohol evaporates © diagram adapted from Flavourtech.com

More and more people are drinking less alcohol. In 2022, half of all adults in the UK bought a no- or low-alcohol product and 85% of UK pubs sell at least one low- or no-alcohol beer. Much of this increase in sales can be attributed to brewers launching products that still taste 'authentic', made using high-quality ingredients and more advanced methods.

Two main methods are currently used for producing alcohol-free drinks: vacuum distillation and reverse osmosis. Generally, manufacturers will make the beverage, such as beer or wine, as usual and then remove the alcohol content.

Vacuum distillation takes place at reduced pressure, which decreases ethanol's boiling point. Alcohol boils at a lower temperature than water, so reducing the temperature means that the ethanol evaporates from the liquid while preserving its flavour. This technique is particularly popular with winemakers. It has two stages: the first takes place at 30°C and strips volatile compounds from the liquid. The second stage at a higher temperature removes the alcohol.

The process takes place inside a stainless-steel column. A series of alternating spinning and stationary cones are attached to its inner wall and on a central rotating shaft inside. The liquid is fed into the top of the column under vacuum while steam enters from below. The spinning cones generate centrifugal force that creates a thin liquid film that moves over the cones, and the volatile compounds evaporate into the steam at low temperatures. The liquid is again passed through the column at a higher temperature to remove the alcohol through evaporation.

Other manufacturers use membranes that allow water and alcohol to flow through them but not flavour compounds, which are larger molecules. This process, called reverse osmosis, is more commonly used to brew beer. To increase the volume once the alcohol has been removed, brewers will add fresh water to the flavoured liquid or distil the water that has been removed and blend it back into the liquid once the ethanol has boiled off.

Brewers also use other methods, such as not adding yeast or using special strains of yeast so that the mixture does not ferment. Another approach is to ferment at low temperatures to produce low amounts of ethanol. However, many of these processes result in dull or little flavour.

As demand grows and well-known drinks manufacturers and premium brands move into the low- or no-alcohol arena, producers are searching for the latest techniques and technologies. Guinness has almost tripled production of its zero-alcohol brand at its Dublin brewery and brewers across the UK and beyond are experimenting with innovative brewing processes. Since January 2023, wine producers across the European Union have been able to produce and market de-alcoholised wine with an alcohol content below the previous minimum threshold of 8.5% ABV. In this way they can meet the demand for non-alcoholic wine and encourage winemakers to innovate further.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