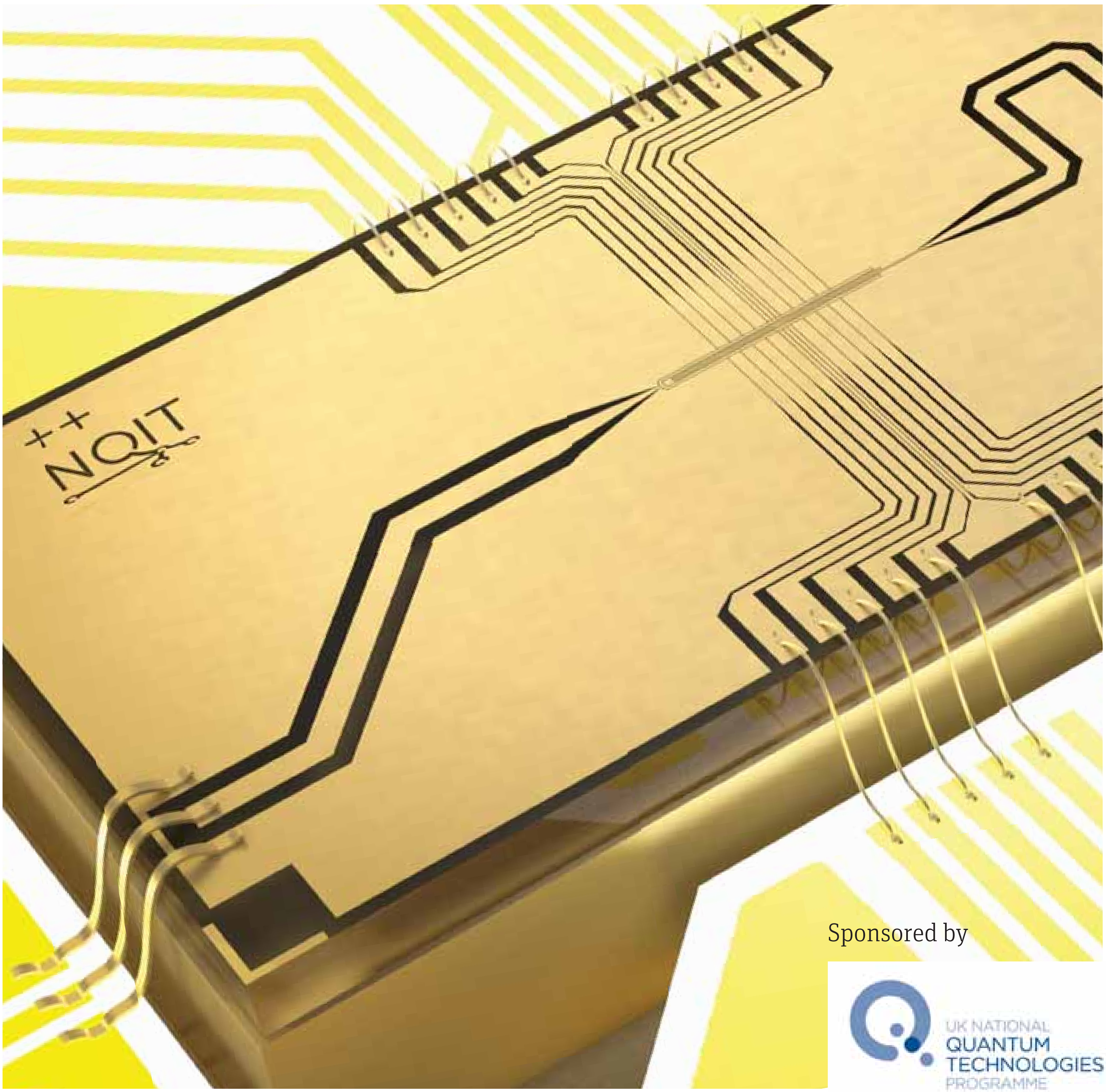
NewStatesman

Quantum technologies

The research behind a revolution



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UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Building an ecosystem for breakthroughs

Patrick Vallance, the government's chief scientific adviser and head of the Government Office for Science, outlines the strategy for investment in new quantum technologies

Navigation systems that can operate without GPS, cameras that can see around corners, gravity sensors that can see through the ground, secure information and connectivity, super-accurate sensors for diagnosis, computers that can model and design new materials. These are some of the possibilities that come from harnessing the curious properties of quantum physics. A particle can appear to be in two places at once, in which two quantum objects can be entangled and the measurement of one tells you about the second even if it is far apart. In this advanced field, information coding doesn't have to be the binary 1 or 0 but can be 1 and 0 at the same time.

The government's ambition is to be at the forefront of cutting-edge quantum technologies to reap their benefits for society. In 2013, the government announced an investment of £270m into developing a National Quantum Technologies Programme over five years, to develop and commercialise quantum technologies, move them out of laboratories into the marketplace, to boost British business and place the UK as a leader in the global supply chain.

In 2016, at the mid-point of the programme, the Government Office for Science published a quantum technologies review, which explored how the UK could benefit from the research, development, and commercialisation of quantum technologies for the economy. Most recently, in the 2018 Autumn Budget, a further £235m was allocated to support quantum technologies, in addition to the £80m extension of the Quantum Technology Hubs. The aim is clear: to capture the ingenuity and creativity of our world-class research base and turn it into commercial advantage and societal benefits. And we are well positioned to be at the forefront of this new age of quantum technologies. In November last year, UK scientists built the world's first quantum compass, a self-contained navigation device that does not rely on external signals and uses ultra-cold atoms rather than GPS satellites.

Of course, others have seen the opportunity too. China is investing billions of dollars and has its sights set on becoming a quantum superpower. The United States has passed legislation, is allocating resources and has created a new sub-committee in its National Science and Technology Council to co-ordinate research effort. Australia and Canada are developing their own ambitious programmes and the EU has established its exciting Quantum Technologies Flagship programme. As always in science, the advances will come from both close collaboration and keen competition, and the UK is good at both. Quantum technology is moving a pure science problem to an engineering challenge where industry, academia and government need to work closely together to achieve innovation. Investing in the skills for a future workforce, ensuring a strong pipeline of STEM and quantum-skilled talent to support demand for these skills, will be essential.

UK scientists have made considerable progress and government support has been fundamental to this success. The digital revolution created devices that impact every part of our lives, though many were hard to predict. Similarly, much of the promise of quantum technologies will only emerge through interactions between scientists, academics and users, brought together by the catalysis of initiatives such as the National Quantum Technologies Programme. The quantum age has the potential to change as much as the digital revolution, in ways that are rapidly emerging.

The UK can lead from the front in a brave new world

Roger McKinlay, challenge director of quantum technologies at UK Research and Innovation, says that science and society should embrace, rather than fear, change

People talk about disruptive technologies as if they spring out of nowhere, like the arrival of a flying saucer in a sci-fi movie. Former Prime Minister Harold Wilson presented the "white heat of technology" as an unstoppable force, partly to sway those in his own party who were resisting change. Sometimes it is convenient to pretend nobody is in control.

Technology may be disruptive, but so is life. Thomas Newcomen's steam engine was not an unstoppable idea. Its success came from the disruption caused by the Black Death. Britain had a labour shortage and automation made good business sense. Continental Europe was not technophobic, but had an abundance of labour and no need for the technology.

We live in an age of disruption and quantum technologies are poised to fill some voids. First is a limitation of classical physics. Our artificial intelligence and data ambitions cannot be met with existing technology. The tiny electron, which brought us the digital revolution, is now too slow and cumbersome to deliver much more. The end is in sight for Moore's Law, the familiar trend of electronics halving in size and cost every couple of years.

We need to find new ways to make computers smaller and faster. To do this we need to exploit more nimble, more sensitive properties of atoms: quantum states. Quantum technologies will also revolutionise cyber security, giving us the ability to distribute cryptographic keys that cannot be intercepted.

The second void to fill is the disruption caused by our ageing society. Healthcare must change. We need imaging techniques that are non-invasive; we need to see things we cannot see today. This will be essential if we are to have the confidence to screen large numbers of people without being misled by costly, potentially dangerous false positives.

The third area is clean growth. We need to know more about our environment, particularly what is going on under our feet. To remove harmful CO_2 we need to find underground spaces for carbon sequestration. Quantum gravity sensing may hold the answer.

The way we distribute power is facing disruption as well. Satellite timing signals are currently used for controlling our grids but these can easily be interfered with. Quantum technology could provide a robust solution in the form of small atomic clocks.

The final area is the future of mobility. Quantum gravity sensors will enable us to map underground hazards such as mineshafts and drains, saving millions of pounds on complex projects such as HS2 and reducing the congestion caused by roadworks in our city centres. Autonomous vehicles will require new "eyes" capable of seeing through smoke and fog. Quantum imaging can help here, and even detect the light scattered from objects just around the corner.

Not surprisingly, all four "voids" are Grand Challenges in the UK Industrial Strategy. These are real problems in search of technological solutions. UK Research and Innovation (UKRI), working with universities and companies, has already invested £400m in the UK National Quantum Technologies Programme.

It is time to take a less hands-off approach to technological development, to harness it to exploit the many forms of disruption life throws at us. The UK National Quantum Technologies Programme is the envy of other nations. As part of our Industrial Strategy, it helped the UK to achieve a unique position of expertise and insight that could be exported elsewhere.

Researchers have found ways to exploit the atomic behaviour of matter and light

QUANTIC

Industry and academia are partnering to explore exciting quantum technologies in computing, sensing, imaging and communications

Quantum solutions to real-life problems

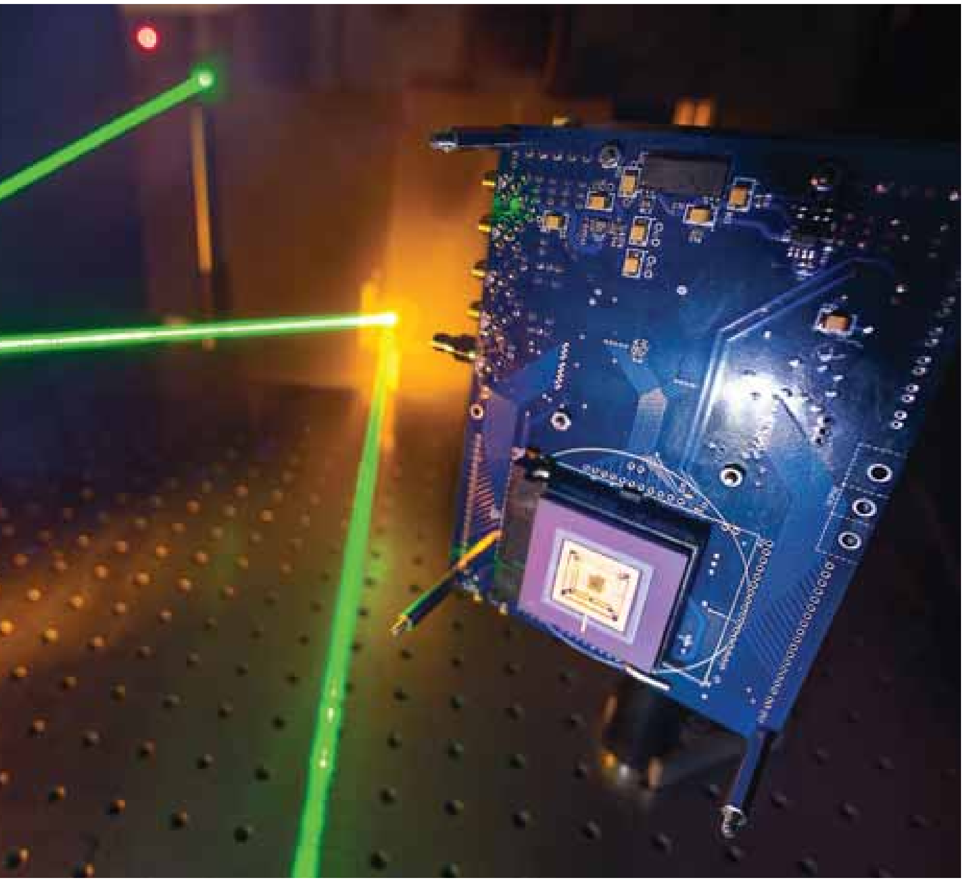
Quantum mechanics, which explains the nature and behaviour of matter and energy at the most basic level, represents one of the most significant scientific breakthrough fields of the 20th and 21st centuries. Adding fresh insight into how electrons, protons, photons and other fundamental particles interact and behave, quantum technologies are those which are able to manipulate and adapt these constituents functionally to fulfil a purpose.

In classical physics, objects exist in a specific place and at a certain time, but in quantum mechanics, they exist in terms of probability; they have a variable chance of being at one point or another. Quantum technologies, then, are those which are able to contain or control this probability.

It makes perfect sense for the United Kingdom to invest in this microscopic revolution that has game-changing capabilities for computing, imaging, sensing and communications technologies. In 2014, the UK government committed £270m into quantum research via the UK National Quantum Technologies Programme, overseen by the Engineering and Physical Sciences Research Council (EPSRC), with the long-term aim of developing, testing and ultimately commercialising quantum technologies. As part of the programme, four quantum technology Hubs, each specialising in a different application of this science, have been established. These are: the Network Quantum Information Technologies (NQIT), QuantIC – the UK Quantum Technology Hub in Quantum Enhanced Imaging, the Quantum Communications Hub, and the Quantum Technology Hub in Sensors and Metrology.

Whilst conventional computers store information in "bits" that exist in only one of two states – different combinations of 1s and 0s are used to represent numbers and letters – a quantum computer stores data in "qubits", which can achieve "superposition", i.e. the feat of existing in two positions at the same time, which means that a qubit can be both a 1 and a 0 simultaneously. Two or more qubits can be in superpositions of correlated states (that is, say, if the first is a "1" then the second is a "0" and vice versa). This is called an "entangled state" and turns out to be a very powerful way to manipulate information. A group of qubits, then, could create a superposition of a practically infinite range of possible combinations, allowing for incredibly fast and parallel calculations to take place.

The key is to identify objects that can be used as qubits, and to have sufficient control over them that they can be manipulated into such states. In the NQIT Hub, one of the leading contenders for encoding qubits is in the nuclear and electronic spins of individual atoms. These atoms are stripped of an



electron and held as ions in an electrical trap, cooled by lasers so that they can "talk" to one another by means of their movements nearer or farther from one another. They are also able to link with remote ions, in separate traps, by means of the emission of single photons that facilitate the entanglement of the distant ions. This forms a basic network architecture that has the potential to be a very powerful quantum computer.

The NQIT Hub, Professor Ian Walmsley claims, is developing the core components for a quantum computer that will "address computational problems that are simply impossible for any current or foreseeable computer". Walmsley, the Provost of Imperial College London as well as director of the Hub, predicts that the NQIT Hub will contribute to producing a machine "that will outperform current computers" in the next five to seven years, and a "fully scalable device that does everything we would like it to do" within the next decade.

Quantum cameras see round corners

Cameras, too, can be enhanced by quantum mechanics. By mapping the time that photons (light particles) take to reach different parts of an object and return to the camera, it is possible to determine depth through 3D imaging. By using light that bounces off walls, floors and other surfaces, it is possible to locate an object that is behind another one. At QuantIC, business development manager Kevin McIver says academics are developing cameras that can actually detect obscured motion. "That's been tested to identify the number of people who might be round the corner, how close to the corner they are, how far away, and in fact some of the results, show that to a 90 per cent accuracy level we can actually identify the difference between people." Such developments, McIver highlights, could be particularly useful within the defence sector – "Is this is a civilian? Is this someone who's carrying a weapon?" – or the automotive industry. He adds: "It's got the potential to see up a road and see round the corner. Is there a car approaching quickly? Is there a child on a bike?"

The thinking behind all of the quantum Hubs, according to Professor Kai Bongs, is focused on finding practical solutions to existing societal problems. Bongs, the director of the UK Quantum Technology Hub for Sensors and Metrology, specialises in driving the translation of gravity sensors into applications across climate change, communications, energy, transport and environmental science. "We're not looking for new physics or new science," he says. "We want to do things which are already proven in the lab and apply them to real-world, real-life problems, accessible to everyone."

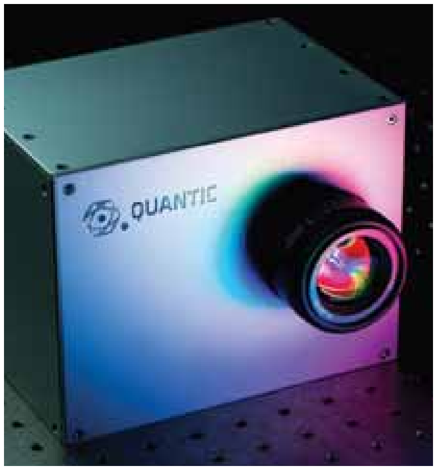
Quantum sensors are able to measure gravity, magnetic and electric fields, and the acceleration and rotation of objects with greater sensitivity, accuracy and stability. Many of them make use of quantum behaviour, such as superposition, and the wave-like properties of atoms. Potential applications for quantum sensors include mapping the locations of tunnels or pipes underground, which could reduce survey times and could detect and characterise objects far deeper than current sensors are able to reach. Bongs says: "Any mass will have a gravitational field around it; our sensors can measure that. It's a way to start looking into the ground and to know what's under it. If you have a leaking water pipe, you might get sink holes or flooding, but if you have water leaking in the ground, that will create more

Key analysis is offered in real time

mass, because it will make the ground wet. It will be heavier and you could see that with a gravity sensor." Being able to detect problems such as these more promptly, Bongs suggests, would help people to maintain and amend complex infrastructure quickly and effectively.

Quantum technologies also have the potential to be used in healthcare. "If you wanted to analyse, understand and design new molecules that might inform new drugs, for example," Walmsley says, "then a quantum computer is the most efficient way to stimulate a quantum system, such as a complex molecule." One of the early expected applications of the hardware is as quantum simulators, which will enable the study and design of new materials and processes, possibly leading to improved treatments.

Magnetic fields produced by the brain can be measured to study the structure and function of the organ in real time. Analysing large amounts of imaging data more quickly and more accurately would enable clinicians to accelerate their diagnoses and further their understanding of biological processes and the effects and unique properties of new medicines.



Quantum cameras can see obscured materials

The success of all of the quantum Hubs is determined in no small part by their collaboration with the private sector. The Quantum Communications Hub, where short-range and long-range communication technologies are being prepared for widespread rollout, has worked with Toshiba to launch fibre-optic-based networks in Cambridge and Bristol, and the Hub has worked with BT to launch a quantum communications link from Cambridge to BT's Adastral Park, near Ipswich on 26 March 2019.

The Hub's director, Professor Tim Spiller, points to the looming threat to current secure communications from the emergence of a powerful quantum computer. Against the backdrop of digitalisation and more people communicating information securely over the internet, it is important to be vigilant about the "shelf life" of that data, and to be careful "about who might be able to intercept it now, and then decrypt it in the future". He says: "If it's information that needs to be kept secure for just a few days, it doesn't matter if someone decrypts it in ten years' time. However, if it's your medical or other important information, it does matter if it is intercepted today and then decrypted in ten, or even 20, years' time, whenever a quantum computer emerges." Quantum-empowered communications could hold the answer. There is the potential to encode information in individual photons, which cannot be measured without disturbing their quantum state, which in turns means that anyone doing so would be detected via this disturbance.

Professor Ian Walmsley says the NQIT, meanwhile, is working to deliver "new, spin-out companies that will begin to take some of the hardware and software forward." It has also partnered with the Quantum Communications Hub's project with BT, with a view to establishing reliable quantum infrastructure. "The likes of BT… have to get fibre-optic cables to 30m households around the UK – that's a civil engineering job which is massive," Bongs affirms.

In developing quantum technologies, Walmsley says that the UK has an advantage in that it "has been able to harness a coherent landscape" for research and development, thanks to its world-class universities with their history of innovation. "It's that coherence that has made sure that the whole is far greater than the sum of its parts." Indeed, the success of the UK National Quantum Technologies Programme to date has led other countries to follow suit. "We were the first programme in the world to consolidate and spearhead investment into quantum technologies," reflects Peter Chua, public engagement and communications officer at QuantIC, "and it's only last year that the European Union announced their own quantum initiative. In terms of foresight, I would definitely say that the UK was one of the first countries to acknowledge and embrace quantum technologies as the way forward."

QUANTIC

NewStatesman
12-13 Essex Street
London, WC2R 3AA
Subscription inquiries:
charlotte.mullock@newstatesman.co.uk

Account Manager
Justin Payne
+44 (0) 20 3096 2273
Commercial Director
Peter Coombs
+44 (0)20 3096 2268

Special Projects Editor
Will Dunn
Special Projects Writers
Augusta Riddy
Rohan Banerjee

Design and Production
Leon Parks

Cover image
Jochen Wolf,
Oxford Ion
Trap Group

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The new quantum revolution

Quantum technologies are a cross-sector revelation, writes George Tuckwell, project lead at Gravity Pioneer

The National Quantum Technologies Showcase in London last year demonstrated the progress arising from the UK government's investment in emerging quantum technologies. A variety of exhibits, from sectors such as transport and space, through to healthcare and civil engineering, all highlighted the progress in quantum technology research and how various industries can use it.

Indeed, the UK has invested large amounts of funding in quantum technology for several years. In 2013, the government announced an investment of £270m for a National Quantum Technologies Programme to give the UK a world-leading position in emerging quantum technology markets and to bring quantum technologies to some of the biggest industries in the country. Since then, several projects have been researching and testing the potential applications of these new quantum technologies and what they can achieve. For UK industry, particularly the service sectors, the potential is really quite exciting.

The Gravity Pioneer project, for example, which Roger McKinlay, the challenge director of quantum technologies at UK Research and Innovation, announced at the showcase, has been developing a new industry of quantum cold-atom sensors that will detect objects beneath the ground better than any current technology. The project has received £6m in research funding from UK Research and Innovation and is led by leading environmental and engineering services company RSK.

Working with leading UK universities and 11 other organisations currently involved in quantum technologies in the UK, the project is developing a commercially relevant device that has the potential to revolutionise understanding of the ground beneath our feet. It is aiming to demonstrate a 2× sensitivity improvement and 10× measurement speed improvement over the industry standard gravity sensor and reduce the need for investigative drilling or digging.

This technology is exciting for several industries. Principal designers, project managers and quantity surveyors, for example, will be able to see sub-surface hazards such as pipes, cables and other buried obstructions long before they become expensive problems to solve. Road networks will not be dug up so often, brownfield land will not be left undeveloped and users will be able to locate forgotten mineshafts, determine the extent of sinkholes and assess the quality of infrastructure without huge economic and societal costs.

The project team is already exploring how this technology can be applied in the civil engineering, aerospace, oil and gas, rail and defence sectors. Further research and innovation will enable refinement and performance improvement of this technology. Recent tests have looked at how quantum gravity sensors could be used to locate buried assets along the railway network. They were able to detect hidden assets currently unlisted on existing asset databases. This is just one example of how industry is beginning to apply quantum technologies in practice. The team is excited about what further research and testing could achieve.

The 2018 National Quantum Technologies Showcase demonstrated a growth in industry participation; more industries than ever before are exploring how quantum technology can be used to revolutionise its products and services. As the potential of quantum technology continues to increase, I would not be surprised to see even more sectors tapping into the advantages of quantum technology at the next one.

UK research and innovation landscape

Research

4 EPSRC Hubs in quantum imaging, quantum sensing, quantum communications and quantum computing and simulation

Skills

3 EPSRC Centres for Doctoral Training

3 EPSRC Training and Skills Hubs in quantum systems engineering

14 EPSRC Fellowships

dstl studentships

Innovation

UKNQT demonstrators

National Quantum Computing Centre
**subject to business case*

Industrial Strategy Challenge Fund

Innovate UK/EPSRC innovation projects and feasibility studies

Infrastructure

NPL Quantum Metrology Institute

EPSRC capital infrastructure

The National Quantum Technologies Showcase 2019

The date has been set for the next Showcase, where you can see the technological progress arising from the National Programme, its relevance to commercial sectors and the collaborative nature of the Programme involving academia, industry and government partners.

Please hold the date:
9 November 2019
Location: **Westminster, London**

Registration will open in May and details of how to register will be available at:
www.uknqt.epsrc.ac.uk/news-and-events/events

If you would like to be added to the Quantum Technologies Showcase mailing list to get the registration link sent to you, please email: **quantumtechnologies@epsrc.ukri.org**