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A user-driven ethos was at the heart of our original proposal for QuantIC and continues to guide every aspect of project delivery. Our mission remains focused on pioneering a range of multidimensional cameras based on quantum principles to create a new UK industrial landscape for imaging systems and their applications.

In response to our growing technology portfolio and the breadth of possible applications and markets, we have expanded the use of our Partnership Resource Fund to support targeted market research to identify the most promising leads and focus our commercialisation efforts. Through our collaborators we have responded to the needs of the market and our work has been widely acclaimed, not only because of its quality but also its relevance to real-world problems and industry.

We have also continued our engagement with the public. Examples of QuantIC’s technology are featured in a permanent public exhibition, “Making the Invisible Visible”, developed in association with, and hosted by, the Glasgow Science Centre. In partnership with the Scottish Schools Education Research Centre (SSERC), we have also run quantum physics workshops and are contributing to the education of the quantum scientists and engineers of tomorrow.

A major focus of our second year was an in depth review of our research and technology programme. The outcome has resulted in the acceleration of the most promising demonstrators with the award of additional funding to support their exploitation in the final years of the programme. Our team of investigators continue to provide not only research excellence but also commitment to developing cutting-edge technology. Within the pages of this report we have highlighted examples of research and innovation excellence that demonstrate the quality of work being conducted by our team.

Year two has been very successful and exciting; we hope you will find this report informative and that it will inspire you to find out more about the project. We look forward to hearing from you.
QuantIC is one of four UK Quantum Technology Hubs established as part of the £270M government investment in the UK National Quantum Technologies Programme (UK-NQTP). The aim of the UK-NQTP is to accelerate the translation of quantum science into economic and societal impact for the benefit of the UK.

The four Hubs in the National Network are:

- QuantIC – UK QT Hub in Enhanced Quantum Imaging
- NQIT – UK QT Hub in Networked Quantum Information
- The UK QT Hub in Quantum Sensors and Metrology
- The UK QT Hub in Quantum Secure Communication

For more information on the UK-NQTP please see [http://uknqt.epsrc.ac.uk](http://uknqt.epsrc.ac.uk)

The vision of the UK National Quantum Technologies Programme is the creation of a coherent quantum technology community where government, academia and industry collaborate to secure a leadership position for the UK in the emerging multi-million pound quantum technology market.

In 2016 the Government Office for Science published a report entitled "The quantum age: technological opportunities". Known as the Blackett Review, the document provides policy recommendations to support the growth of quantum technologies in the UK based on the significant economic potential of the field.

The UK has a unique opportunity to lead in the development and commercialisation of emerging quantum technologies to realise real societal and economic benefits from this investment.

Over the next five to ten years, quantum enhanced imaging technologies will deliver economic and societal benefits in areas such as security, medical imaging, scientific instrumentation, energy and defence.

Our vision, shaped in collaboration with over 40 industry partners, is to pioneer a family of multidimensional cameras operating across a range of wavelengths, time-scales and length-scales, creating a new industrial landscape for imaging systems and their applications in the UK. QuantIC’s approach to user engagement and innovation includes a strategy aimed at exploring with industry the potential for quantum technologies to improve products and processes in the imaging sector.

Industrial representation is at the core of our management structure. The Market Opportunities Panel, comprising 18 industrial partners, directs the strategic investment of the £4M Partnership Resource Fund (PRF). The PRF has been designed as a flexible and responsive tool to support the translation of QuantIC’s research outcomes into industrial applications and commercial opportunities. In addition to feasibility studies and technology development projects, QuantIC’s PRF also supports the secondment of staff to aid knowledge exchange between academia and industry. A snapshot of our user engagement activities to date and a selection of case studies of funded PRF projects are reported in the innovation section of this annual report.

The Hub is led by Professor Steve Beaumont, QuantIC’s Director, and Professor Miles Padgett, QuantIC’s Principal Investigator and Scientific Lead. The day to day operation of the Hub is supported by a growing and dedicated central team to ensure smooth operation and to appropriately resource our outreach and industrial engagement activities.

QuantIC’s technical programme is delivered through four interlinked work packages (WPs). The first three work packages cover system development, focusing on quantum imaging with correlation (WP1), timing (WP2) and squeezing (WP3), whilst WP4 focuses on the development of components such as sources and detectors. Imaging with correlation (WP1) exploits the quantum-inspired correlation between image and source to realise single-pixel cameras and sub-shot noise imaging systems. Imaging with timing (WP2) exploits the time correlation between source and detected signal to provide range-gated and 3D imaging functionality. Quantum imaging with squeezing (WP3) exploits the number and phase correlations inherent in parametric light to provide ultra-low noise/power transmission imaging, fluorescent gain imaging and phase sensing (for biological and gravitational field imaging).

The systems work packages will build on a set of underpinning components developed in WP4 and including world-leading quantum and classical correlated source technologies, single photon sensitive detectors, timing arrays and electronic readout technologies. Detailed overviews of each work package can be found in the Technology Development section of this report.
Since our inception in December 2014, we have focused on our mission to deliver improved imaging technology to users by translating cutting edge research into prototype cameras. After two years on this journey, QuantIC has engaged with over 70 companies and held more than 50 industry visits. Within the same period, the Hub has invested £1M from its Partnership Resource Fund (PRF) in 21 industry-led projects leveraging over £600K from partners.

Year two saw the introduction of the QuantIC Industrial Studentships. We awarded £290K across 8 industrially-led projects and leveraged £370K of industrial support. All projects are aimed at translating technology into real world applications and engaging students on projects at the interface between academia and industry, training the quantum pioneers of tomorrow.

During 2016 we furthered our user and stakeholder engagement by organising a variety of industry-focused workshops, some in collaboration with external partners. For example we co-sponsored a workshop with QinetiQ at their Malvern site that has since resulted in stronger links between the security and defence sector and QuantIC, generating new project ideas and PhD studentships.

Our technology has been further developed with input from industrial partners and users. As a result of our year two review, we have both expanded and refocused our technology development programme.

Our Gas-Sight project in collaboration with M Squared Lasers has progressed from a Phase 1 PRF Feasibility Study to a Phase 2 PRF Demonstrator Project, which will see the development of a prototype (TRL 6/7) with improved range and sensitivity. A number of current PRF Feasibility Studies are producing positive results and we fully expect them to progress to Demonstrator Projects (Phase 2) in early 2017.

The quality of our research has been internationally recognised; our academics have delivered 73 talks at international conferences and published 45 papers in high-level journals in our second year.

Our permanent exhibition on quantum imaging was opened at the Glasgow Science Centre in April and has already been seen by over one hundred and fifty thousand visitors. We expanded our partnership with the Scottish Schools Education Resource Centre and also sponsored a quantum summer school at the University of Bristol to lay the groundwork for the next generation of quantum technologists.

The QuantIC Innovation Space was officially opened in November 2016 and the Hub made its first foray into exhibiting at international industry events such as SPIE Security and Defence. The Hub also contributed nine technology demonstrators at the second National Quantum Technologies Showcase.

During its first two years of operation QuantIC has made great strides in achieving its objectives. We look forward to the next three years that will see delivery of our technology into commercial products.
INNOVATION

Since our inception in December 2014 QuantIC has engaged with over 70 companies and held more than 50 industry visits. We have advanced the commercialisation of our technology by investing £1M in 21 projects and leveraged £627K from industry. During the last year we have awarded £290K to support 8 industrially-led studentships and leveraged £370K of industrial support.

QuantIC is translating technology from academia into commercially attractive quantum enhanced imaging products and systems. We achieve this objective through the following mechanisms:
• Partnering with industry on joint development projects,
• Undertaking prototype development within an individual university,
• Launching market studies to qualify business opportunities.

Key to these initiatives, is our £4M Partnership Resource Fund (PRF). Applications to the fund are assessed by our Market Opportunities Panel which consists of experienced individuals from across industry including BP, e2v, Leonardo, M Squared Lasers, Thales UK, KTN, Innovate UK, Dstl, Renishaw and STMicroelectronics. The key assessment criteria for projects is an attractive business proposition with a route to exploitation for an emerging technology in the field of quantum imaging.

Our PRF Feasibility Studies (Phase 1) are small-scale projects aimed at determining whether a technology has the potential to offer a competitive edge in terms of functionality, performance or cost reduction while our larger PRF Demonstrator Projects (Phase 2) are targeted at progressing the development of quantum enhanced imaging technologies to TRL level 6 or even 7.

In 2016 the Market Opportunities Panel approved fifteen new awards with a total project value of over £832K, leveraging £466K of industrial contribution. These awards build on the six projects approved in our first year of operation, bringing our total funded portfolio to over £1,047K with a total £627K from industry. We are excited to see the potential for a number of our existing studies progress to larger demonstrator projects.

Through the PRF we have had the opportunity to engage with companies including Aralia Systems, Bridgeporth, Chromacity, Gooch and Housego, Horiba Jobin Yvon IBH, Kromek*, Leonardo*, Lockheed Martin, M Squared Lasers*, QMC, STMicroelectronics, and Thales UK.

A number of these projects have resulted in the early stage development of potential new products, including:
• “Wee-g”, a new microelectromechanical (MEMs) gravimeter led by the University of Glasgow;
• “Gas-Sight” a low-cost camera for gas imaging, developed in partnership with M Squared Lasers;
• a new polarisation control system for improved machining in partnership with Gooch and Housego;
• a new multiplexed imaging system for life sciences in partnership with Horiba Jobin Yvon IBH.

For more information on PRF calls and application process visit https://quantic.ac.uk/innovation/partnership-resources.

QUANTIC INNOVATION SPACE

Officially opened in November 2016, the QuantIC Innovation Space is an integral part of QuantIC’s operations. The offices host the central Hub team and offer a space where academics and industrialists can co-locate to accelerate technology development and exploitation. The laboratories are used for collaborative industry-academia projects and for hosting working technology demonstrators from across the Hub.

Located above the James Watt Nanofabrication Centre at the University of Glasgow, the space was funded by a £3M award from the Scottish Funding Council’s Strategic Investments. The QuantIC Innovation space is currently hosting staff and projects from M Squared Lasers, Chromacity and Bridgeporth.

The Innovation Space laboratories and meeting space have also provided an ideal environment to showcase QuantIC technologies through working demonstrators during key events including visits from companies and government ministers.

* Indicates more than one funded PRF project
The ability to know what is hidden around a corner or behind a wall could provide a crucial advantage in many situations, from collision avoidance to search and rescue for emergency services.

QuantIC researchers are working with global industry leader Thales UK to make this a reality. Under a Centre for Defence and Enterprise Phase 1 project and a QuantIC PRF Feasibility Study, the team demonstrated that single photon counting technology can be harnessed to detect motion and even precisely locate the position of moving objects that are hidden behind a corner from a 50+ m stand-off distance.

Thales UK has brought considerable expertise in the design of imaging systems to the project and helped in identifying potential applications for this technology to offer competitive advantage in the defence, security and transportation sectors.

As a result of this success QuantIC has approved a Phase 2 PRF Demonstrator Project with Thales UK and Heriot-Watt University to further develop the technology to TRL 6. This prototype will be eye-safe, portable and capable of detecting motion and locating the position of a moving object hidden behind a corner at a stand-off distance greater than 100m.

We expect the demonstrator to work in real-time with an update rate of 1 second or less. Our camera will be based on single photon counting technology. However, we will also implement our system using Thales UK LIDAR technology, which offers an accelerated route to market.

WHAT’S INSIDE THAT BUILDING?

A collaboration with Thales UK supported by Centre for Defence and Enterprise and Partnership Resource Fund

Photo: Prototype camera from the University of Heriot-Watt exhibited at the Glasgow Science Centre.
Video surveillance is becoming an indispensable tool to ensure both personal and public safety. Common applications include monitoring of critical infrastructure, highways, financial institutions, airports and public transport as well as private property.

Funded under a Partnership Resource Fund (PRF) Feasibility Study (Phase 1), QuantIC researchers are working with security company Aralia Systems to investigate LED visible light systems for covert automated video surveillance. Recent advances in visible light sources and sensors present the potential for extremely small modules offering low-cost and covert imaging of many parallel video images within a single system.

Aralia Systems is a UK SME with strong links to both North America and Asia. It was the first company in the world to offer video analytics and has been supplying governments and agencies with these capabilities since 1998. Aralia Systems is unique as it provides all aspects of the software needed to implement a physical security system. The company’s main markets are the surveillance of urban areas, transportation networks and critical infrastructure.

Aralia Systems has developed a covert infrared imaging system based around a photometric stereo concept. Such imaging allows reconstruction of the topology of the scene and greatly improves the automated analysis task. The use of visible LED sources offers significant cost benefits and covertness, whilst also providing the opportunity for further functionality including LiFi communications and position sensing.

A prototype has been built and evaluated using high-speed LED sources developed under the QuantIC programme. The results from this project are extremely positive, successfully demonstrating the potential for this technology by capturing topological information at 60 frames per second in both static and dynamic scenarios. It has also incorporated data signals on top of the imaging signals.

Based on the success of the PRF Phase 1 Feasibility Study, Aralia Systems has successfully secured a PRF Demonstrator Project (Phase 2) aimed at building a TRL 6 prototype system incorporating photometric stereo imaging, indoor navigation and data communications using a single LED illumination infrastructure.

Fluorescence provides a multidimensional signature of a molecule and is widely used for analysis and research across the globe. Sequencing the human genome and disease diagnostics are just two of the many important applications where fluorescence has made its mark.

Horiba Jobin Yvon IBH, the Glasgow-based subsidiary of the Japan-headquartered Horiba Group, has entered into a development partnership with researchers at QuantIC. Funded under a QuantIC Partnership Resource Fund (PRF) Feasibility Study (Phase 1), the project is developing a novel multiplexed, time-correlated single-photon timing fluorescence system.

The fluorescence signature of a molecule carries information that includes the wavelengths of excitation and emission (colour), the intensity of the emitted light (brightness), the characteristic time for emission (decay time), polarisation (alignment), position (image) and yield (efficiency). However, at present all commercially available fluorescence instrumentation accesses only a small fraction of this information and requires many sequential measurements over a long period of time to build up a complete molecular fluorescence signature.

In the last four decades Horiba Jobin Yvon IBH has pioneered advances in time-correlated single-photon correlation technology, for example developing picosecond-scale diode light sources suitable for the ultrafast timescale on which fluorescence takes place, and deep-ultraviolet LEDs for protein analysis. The next step is targeted at implementing new Single Photon Avalanche Diode technology developed by QuantIC in collaboration with STMicroelectronics, to obtain a multiplexed version of the existing Horiba Jobin Yvon IBH technology.

Results from this feasibility study are very encouraging and Horiba has secured a PRF Demonstrator Project (Phase 2) to construct a prototype system with capabilities that surpass current technology by several orders of magnitude in terms of data acquisition and processing speed.

Photo: Micro-LEDs technology from the University of Strathclyde.
How can one detect and image invisible gases? Although many gases are invisible to the naked eye, they do interact with light, just not at wavelengths one can see. The key to imaging invisible gases is making a camera that can see at the correct wavelength.

The global gas sensing market was estimated at USD 1.78 billion in 2013 and is projected to be worth USD 2.32 billion by 2018. There is a gap in the market for a low-cost, small-sized, low-power and highly portable remote gas detection system.

During year one of the project, QuantIC, together with M Squared Lasers, investigated the feasibility of a new infrared imaging technology, a Single-Pixel Camera (SPC), for detecting gas leaks. A prototype camera was developed at the University of Glasgow. Gas-Sight is based on structured illumination of laser light, tuned to a methane absorption band, and a single infrared detector. The camera has successfully detected a small, real-time gas leak of 0.5 litres/min in a laboratory setting. A colour coded gas map overlaid onto a visible camera image helps the operator locate the source of the leak. Gas-Sight offers the potential for a lower cost and more compact gas detection system than currently available. Present limitations of the camera include the distance over which gas can be detected, currently demonstrated at one metre, and sensitivity to a single type of gas, currently methane. The prototype camera will be exhibited by M Squared Lasers at Photonics West 2017 in San Francisco. Industry members from oil and gas, security and defence, agriculture and additive manufacturing have already expressed interest in this technology.

Based on the positive results of the PRF Feasibility Study, a Phase 2 PRF Demonstrator Project has been approved to build a portable prototype capable of detecting at a range of more than 3m. This advanced prototype will utilise a new laser source to broaden the spectrum of gases that can be detected.
WORK PACKAGE 1

Working in collaboration with M Squared Lasers we are developing “Gas-Sight”, a camera that images invisible gases. The concept uses a single pixel detector and structured illumination to image methane gas at video rates (see innovation case study on page 19).

Single-pixel camera (SPC) technology is also at the core of a low-cost “single pixel 3D ranging camera” demonstrator developed in partnership with Leonardo (formerly Selex-ES) (see paper highlight) [M.-J. Sun, et al., Nat. Commun., 2016, 7, 12010]. Both demonstrators rely on the single pixel camera technology (see technology highlight). This year QuantIC has also worked with collaborating groups to extend the single pixel camera to the terahertz regime [R. I. Stantchev, et al., Sci. Advan., 2016, 2(6), e1600190].

Conventional imaging systems rely on a light source to illuminate the scene and a camera system to collect the back-scattered light after interaction with an object. This combination provides an image. In these conventional systems the wavelength of the light illuminating

WHAT IS A SINGLE PIXEL CAMERA?

In essence a Single Pixel Camera (SPC) resembles a data projector where the light source is replaced by a single element (pixel) detector which measures the total power transmitted through a series of binary masks superimposed upon the scene. Since the design of each of these masks is known by measuring the transmitted power associated with each mask, data inversion enables the image of the scene to be deduced [Edgar, et al. Sci. Rep., 5:10909, 2015].

The main advantages of the single pixel approach are in its lower cost and the ability to design cameras that can access wavelength ranges where conventional multipixel arrays are extremely expensive or even unobtainable.

https://www.youtube.com/watch?v=y-jIzuHBJTo
QuantIC has demonstrated a "wavelength transformation" demonstrator utilising the concept of "Ghost Imaging" (see technology highlight). This allows us to illuminate the object with infrared light but collect the image in the visible range using a high performance visible camera. A novel experimental configuration for the "wavelength transformation" technology has already been demonstrated where a microscope image has been obtained from visible photons by illuminating an object with infrared illumination. [R. S. Aspden, et al., Optica, 2015, 2(11), 1049] (see paper highlight).

At QuantIC we are also developing algorithms for image search and recognition. Single-pixel cameras use black and white patterns to illuminate an object. By using a small amount of prior information about the sought objects, we can find greyscale orthogonal pattern bases that are tailored to particular sets of images. This allows us to find and recognise objects faster. We have applied our techniques to recognising many sets of objects, but, in particular, face recognition. We are able to create a 1024 pixel image of a face from only 100 single measurements, i.e. a compression of 90%.

WHAT IS GHOST IMAGING?

Ghost imaging systems use two identical illumination sources. One source is used to illuminate the object and the other source is recorded by the camera. In the quantum regime, these two light sources are identical even at the level of individual photons (produced using a method called parametric down conversion). Whenever a photon striking the object is back reflected, the camera takes an image of the identical photon in the other beam. After many such events the sum of all these individual photons reveals an image of the object, even though none of the photons recorded by the camera has ever interacted with the object itself.

QuantIC has developed a ghost imaging technique where the photon correlated light sources are at different wavelengths, one in the infrared and one in the visible. This allows the object to be illuminated in the infrared and the images to be recorded in the visible spectrum.


Image retrodiction at low light levels

Imaging technologies working at very low light levels acquire data by counting the number of photons impinging on each pixel. Especially in cases with, on average, less than one photocount per pixel, the resulting images are heavily corrupted by Poissonian noise. To tackle this problem, we use methods from Bayesian statistics to retrodict the spatial intensity distribution responsible for the photocount measurements. Unlike the usual photon-limited image denoising algorithms, we calculate the full probability distributions for the intensities at each pixel. The knowledge of these probability distributions helps to assess the validity of results from image analysis using data corrupted by Poisson noise with low photon-count numbers and dark counts.

MATHIAS SOLLERATZS, DOMINIC SEPPING, AND STEVEN R. D. BENTON

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HOW CAN A CAMERA SEE AROUND A CORNER?

In this application a pulsed laser is used to illuminate a spot on the floor some distance ahead of the camera. Light is scattered from this spot and strikes the object that is hidden. Light is then backscattered from the object back into the field of view of the camera where it is scattered (again) from a surface. The extreme single-photon sensitivity of the camera means that this triple-scattered light is still of an intensity that can be detected. This triple scattered light is imaged as a curve of light on the surface, the centre of curvature from which the complex position of the object (c.f. the ripples on a pond). Although recovering the detailed image of the hidden object is as yet beyond the computational power of the analysis, the size and speed of object or objects can be clearly identified.

https://www.youtube.com/watch?v=cDbGFT5rM0I

The ability to detect motion and track a moving object hidden around a corner or behind a wall provides a crucial advantage when physically going through obstacles is impossible or dangerous. Previous methods have demonstrated that it is possible to reconstruct the shape of an object hidden from view. However, these methods do not enable the tracking of movement in real time. We demonstrate a compact non-line-of-sight laser ranging technology that relies on the ability to use light around an obstacle to scatter it and then detect the return signal from a hidden object. Using a powerful compact avalanche diode camera (SPAD) we follow the movement of an object and provide a definition of the state vector in terms of measurable quantities by decomposing these column operators into observables. The technique we propose renders very-large-scale quantum states significantly more accessible in the laboratory, as we demonstrate by experimentally characterizing a 100,000-dimensional entangled state. This represents an improvement of two orders of magnitude with respect to previous phase-and-amplitude characterizations of discrete entangled states.


direct measurement of large-scale quantum states via expectation values of non-Hermitian matrices

In quantum mechanics, predictions are made by way of calculating expectation values of observables, which take the form of Hermitian operators. Non-Hermitian operators, however, are not necessarily devoid of physical significance, and they can play a crucial role in the characterization of quantum states. Here we show that the expectation values of a particular set of non-Hermitian matrices, which we call column operators, provide a definition of the state vector in terms of measurable quantities and are, therefore, accessible in the laboratory.

The performance of the camera has improved since our original publication [C. Gariepy, et al., Nat. Photon., 2016, 10, 23] (see paper highlight) and recently demonstrated tracking of people around a corner at a stand-off distance of 50m. For more information on how a camera can see around a corner see technology highlight.

Further applications for cameras that detect single photons with high temporal resolution, high quantum efficiency, and low-noise performance are fluorescence microscopy, quantum imaging, range finding, and low-light level surveillance. At QuantIC we are exploring time resolved images to see through fog and other atmospheric obscurations. It is estimated that the loss in pilot visibility associated with the dust cloud created by a helicopter landing costs the U.S. around $100 million per year. This technology also has applications for autonomous vehicles and advanced driver-assistance systems. Our technology was recently part of a field imaging trial in the Swiss Alps aimed at benchmarking our prototype camera against real world requirements.

WORK PACKAGE 2

QuantIC is developing cameras that, in addition to the intensity of each pixel, can measure the arrival time of the individual photons. When using a pulsed illumination source, the arrival time gives the time-of-flight from source to object and hence the distance of objects at each individual pixel. Our cameras have individual photon-counting pixels that allow us on the one hand to capture extremely low light intensities (at the single photon level) and on the other hand to obtain picosecond temporal precision. These two attributes taken together allow the capture of high-speed action with a million-fold increase in frame rate when compared to the best commercial cameras. The primary demonstration has been the concept of using a time resolved camera to detect objects outwith the line of sight, e.g. hidden behind a corner.

The “hidden object tracker” has attracted considerable user interest and industrial traction. Future development of this demonstrator will be funded by the Centre for Defence Enterprise and Partnership Resource Fund in collaboration with Thales UK (see innovation case study at page 12). The performance of the camera has improved since our original publication [C. Gariepy, et al., Nat. Photon., 2016, 10, 23] (see paper highlight) and recently demonstrated tracking of people around a corner at a stand-off distance of 50m. For more information on how a camera can see around a corner see technology highlight.

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In this application a pulsed laser is used to illuminate a spot on the floor some distance ahead of the camera. Light is scattered from this spot and strikes the object that is hidden. Light is then backscattered from the object back into the field of view of the camera where it is scattered (again) from a surface. The extreme single-photon sensitivity of the camera means that this triple-scattered light is still of an intensity that can be detected. This triple scattered light is imaged as a curve of light on the surface, the centre of curvature from which the complex position of the object (c.f. the ripples on a pond). Although recovering the detailed image of the hidden object is as yet beyond the computational power of the analysis, the size and speed of object or objects can be clearly identified.

https://www.youtube.com/watch?v=cDbGFT5rM0I

The ability to detect motion and track a moving object hidden around a corner or behind a wall provides a crucial advantage when physically going through obstacles is impossible or dangerous. Previous methods have demonstrated that it is possible to reconstruct the shape of an object hidden from view. However, these methods do not enable the tracking of movement in real time. We demonstrate a compact non-line-of-sight laser ranging technology that relies on the ability to use light around an obstacle to scatter it and then detect the return signal from a hidden object. Using a powerful compact avalanche diode camera (SPAD) we follow the movement of an object and provide a definition of the state vector in terms of measurable quantities by decomposing these column operators into observables. The technique we propose renders very-large-scale quantum states significantly more accessible in the laboratory, as we demonstrate by experimentally characterizing a 100,000-dimensional entangled state. This represents an improvement of two orders of magnitude with respect to previous phase-and-amplitude characterizations of discrete entangled states.

MaterialPhotronics
HOW DOES A COVERT QUANTUM RANGEFINDER WORK?

Laser rangefinders measure distance by measuring the time it takes for a light pulse to reflect from an object and return to the source.

A quantum rangefinder uses a highly efficient photon-pair source that emits two photons into two modes at exactly the same time. One of these photons acts as a trigger to the user, alerting them to the emission of a second photon. This knowledge of exactly when the photon is produced provides additional information allowing the ranging of objects with ultra-low intensity.

On the other hand, since the object that is being ranged has no knowledge of this emission time, they cannot distinguish between the illumination and the thermal background. The ranging of the object then becomes covert.

Commercially available scientific cameras do not have all the desired features at once: electron multiplying cameras (EMCCD) have a high quantum efficiency but relatively long exposures; intensified cameras (ICCD) provide very short exposure times and can be triggered at high repetition rates, but their single photon efficiency is very low. A very attractive solution is a camera based on single photon avalanche detector (SPAD) arrays. Our goal is to establish SPAD cameras as an alternative to EMCCDs and ICCDs.

The "quantum rangefinder" has been progressing through year two with the development of a high-efficiency correlated photon source which will enable covert ranging using extremely low-light levels. The optomechanical design for the rangefinder is complete and will be built and tested in year three. The electronic has been designed and built as a self-contained 55x170x220 mm box, which has proved reliable in a laboratory environment. For more information on how a quantum rangefinder works see the technology highlight.

Photo: Shot taken at field trials of QuantiC technology in the Swiss Alps.
WHAT IS SUB SHOT-NOISE IMAGING?

In conventional illumination, the number of photons recorded in any one data bin (image or spectrum) is subject to a shot-noise variation equal to the square root of the number of photons recorded. This noise floor represents the quantum limit of classical measurement. The use of correlated beams allows this limit to be overcome. Since the shot-noise is identical on the two beams, dividing the number of photons measured in one beam by the number of photons measured in the other yields a unity ratio. This ratio is noise free. A slight absorption in one beam appears as a change in this ratio and hence can be detected even in the presence of shot-noise. The extent to which this noise reduction can be implemented is critically dependent upon the measurement efficiency. Meaningful reductions in noise require a measurement efficiency in excess of 90%. This high efficiency requirement applies not just to the detectors but to the sources too, hence the development within QuantIC of high-efficiency photon-pair sources.

emission microscopy exploits stimulated-emission as a contrast mechanism for optical microscopy, allowing background-free imaging of these “dark” molecules. Crucially, the classical performance of this technique is shot-noise limited, and hence suitable for quantum enhancement, providing an ideal test case for the first demonstration of sub-standard quantum limit (SQL) measurement of a biological system. Stimulated-emission microscopy requires the accurate resolution of minuscule changes in the intensity of a probe field. The current sensitivity of such microscopes is limited by the shot-noise of the probe light. At the shot-noise limit, the fluctuations in the light intensity are a direct consequence of the quantum nature of light, with quantum mechanical enhancement being the only path to increased sensitivity. Quantum “squeezing” of the probe allows the intensity noise floor to be robustly reduced below the shot-noise limit. The integration of squeezed light into the microscope will improve the resolution of the technique beyond the sub-standard quantum limit into a new quantum-enhanced stimulated-emission microscopy.

To open up applications in bio-imaging, a highly “squeezed pulsed light source” suitable for pump-probe microscopy has been developed. While the generation of squeezing in femtosecond pulses is a challenging problem, we have inferred 2.0 dB of quantum noise suppression in laboratory measurements of the light source. The observed noise suppression is now sufficient to realise a prototype microscope operating below...
delivered valuable tools to microscopy. Non-linear physics has already achieved a noise level corresponding to the standard quantum limit, with an efficiency of 60%.

In parallel with these experimental efforts, theoretical studies have focused on the formulation of a complete theory of quantum imaging, based on multi-parameter estimation theory. While single-phase estimation captures a wide range of scenarios, high-level applications such as microscopy, spectroscopy, and optical, electromagnetic, or gravitational field imaging intrinsically involve multiple parameters that should be estimated simultaneously (see paper highlight) [T. Baumgratz, et al., Phys. Rev. Lett., 2016, 116 (3)].

Conventional wisdom suggests a sensor built with classical light sources achieves a noise level corresponding to the square root of the number of photons measured. However, non-linear interactions allow for measurement sensitivities that scale well beyond the traditional standard quantum limit. Non-linear physics has already delivered valuable tools to microscopy and sensing, most notably techniques based on two-photon absorption or Raman scattering. The non-linear "Chi-3-sensor" currently under development at QuantIC, offers a complementary approach with distinct advantages in certain sensor configurations (e.g. chip-based devices) or for particular samples (e.g. those that cannot absorb light). This technique will also be of value in the accurate characterisation of the non-linear properties of industrially relevant materials, as well as in biological applications. An example of the latter is the potential development of a diagnostic technique based on the changes in Chi-3 properties exhibited by cells during the early stages of cancer malignancy.

Measurement of gravity enables the local mass density to be imaged. Gravity surveys are regularly used for oil and gas prospecting, environmental monitoring and security applications. Current state-of-the-art instruments are high-performance but high-cost. There is a gap in the market for cheaper, highly sensitive devices that provide high resolution gravity maps at a fraction of the cost. A relative gravimeter monitors the local change of gravity by sensing the position of a mass on a spring. Changes in the local gravitational acceleration, due for example to mass anomalies associated with oil reserves, change the vertical height of the mass. Our MEMS-based gravimeter, "Wee-g"; is an all silicon micro-fabricated device with a proof mass of 0.02 mg. (For more details on what a MEMS is, see technology highlight). The MEMS device is read out with an optical sensor, enhancing sensitivity over traditional capacitive readouts and providing a system immune to electromagnetic interference [R. Middlemiss, et al., Nature, 2016, 531, 585] (see paper highlight). During the last year, we have advanced the development of our technology by incorporating control electronics to deliver a portable prototype suitable for field testing. The complete demonstrator has attracted considerable user interest with industrially sponsored collaborations with Dstl, Clyde Space, (QinetiQ) and Schlumberger and a partnership resource project with Bridgeporth for Schlumberger and a partnership resource project with Bridgeporth for a proof mass of 0.02 mg. (For more details on what a MEMS is, see technology highlight). During the last year, we have advanced the development of our technology by incorporating control electronics to deliver a portable prototype suitable for field testing. The complete demonstrator has attracted considerable user interest with industrially sponsored collaborations with Dstl, Clyde Space, (QinetiQ) and Schlumberger and a partnership resource project with Bridgeporth for Schlumberger and a partnership resource project with Bridgeporth for field trial and benchmarking of the complete MEMS gravimeter. The MEMS device is an all silicon micro-fabricated device. Many sensor systems are formed from mechanical components which bend, flex or move in other ways. Such components include temperature and pressure sensors or accelerometers. The latter is the core of our MEMS gravimeter. The small size and low cost of MEMS gravimeters—found in consumer electronics (e.g. those that cannot absorb light). This is a universally predictable gravitational signal that requires both high sensitivity and high stability over time scales of several days to measure.

All present gravimeters, however, have limitations of high cost (more than 100,000 US dollars) and high mass (more than 8 kilograms). Here we present a microelectromechanical system (MEMS) device with a sensitivity of 40 microgal per hertz; only a few cubic centimetres in size. We use it to measure the Earth tides, revealing the long-term stability of our instrument compared to any other MEMS device. MEMS accelerometers—found in most smart phones—can be mass-produced remarkably cheaply, but none are stable enough to be called a gravimeter. Our device has thus made the transition from accelerometer to gravimeter. The small size and low cost of MEMS gravimeters suggests many applications in gravity mapping. For example, it could be mounted on a drone instead of low-flying aircraft for distributed terrain surveying and exploration, deployed to monitor volcanoes, or built into multi-pixel density-contrast imaging arrays.

WHAT IS A MEMS DEVICE?

Many sensor systems are formed from mechanical components which bend, flex or move in other ways. Such components include temperature and pressure sensors or accelerometers. The latter is the core component of the MEMS "Wee-g", where part of the silicon forms a mass attached to a spring. Sensor can be fabricated in bulk on silicon wafers making manufacture scalable. This process also eliminated joints and bonds dramatically improving the long term stability of the sensor.
The technology breakthrough was the implementation of SPADs in CMOS in 2003. A SPAD is a reverse-biased diode junction operating above the breakdown voltage in the so-called Geiger mode. SPAD devices were originally proposed in older 0.8 µm or 0.35 µm CMOS technology nodes but have since been rapidly integrated in nanometer geometries. We have built on the success of the CMOS SPAD arrays delivered in year one and designed new chips with higher fill factor that will underpin improved performances of demonstrators in WP2 [I. Gyongy, et al., Electron Devices Meeting (IEDM), 2016 IEEE International]. QuantIC has designed and manufactured two new CMOS SPAD camera chips in both front-side illuminated and stacked 3D technologies. “QuantICAM 3” is adopting the most advanced CMOS technology node-to-date. The first results are now available from the QuantICAM sensors showing that the SPADs are operating with unparalleled low noise performance.

QuantIC is also developing some of the world’s most advanced infrared photon counting technologies, namely superconducting nanowire single photon detectors (SNSPD) [I. Yamashita, et al., Sci. Rep., 2016, 6, 35240]. We have devised a stable electron beam lithography process for device fabrication. Four pixel devices suitable for fibre coupling have been benchmarked at low temperatures. Given their low temperature operation, the deployability of these detectors outside the scientific realm is dependent on the availability of compact and user-friendly cooling technology.

QuantIC is working with the team at Rutherford Appleton Laboratory to construct the world’s first superconducting single photon detector system based around miniaturised 4 K closed-cycle cooling. The prototype detector was developed during the first 18 months of QuantIC and it features an integrated fibre coupled SNSPD, suitable for photon counting and imaging applications. An example application currently being explored is the in-situ monitoring of the efficacy of photodynamic cancer therapies. Photodynamic therapy is used to treat a variety of cancers and other non-oncological pathologies, such as age-related macular degeneration. The main advantage is its low overall toxicity but widespread use is currently limited by the difficulty in accurately quantifying the effective treatment dose. [M. M.

LED devices are becoming a standard lighting technology for domestic, automotive and industrial applications due to their long lifetimes and high electrical-optical conversion efficiencies. These devices typically operate in the continuous illumination regime with little extra functionality. At QuantIC we are developing next-generation LED micro-displays that can transmit data, send ultra-short pulses of light into an environment and track objects in a room, or on a microscope slide.

Our micro-LED displays are fabricated using Gallium Nitride with pixel sizes of a few tens to hundreds of micrometres across. This small size allows each pixel to be switched at GHz rates. Devices can be made with hundreds of individually controllable pixels, allowing for extremely fast pattern generation and data projection. The key to harnessing the high speed of these arrays is the integration of the LED chips with dedicated CMOS electronics drivers. The “micro-LED arrays” have been applied to a new LED ambient lighting demonstrator that allows objects to determine their position within a room and can be coupled with fast data transmission (see innovation case study on page 14).

Most optical filters are based upon coloured glasses or dielectric thin films. At QuantIC we are developing an alternative approach where the optical properties of the filter depend upon nanostructures that are fabricated on the optical surface. These devices are known as “plasmonic filters” and present the advantage of working at wavelengths that standard technologies, such as dielectric films, cannot reach. Compared with dielectric films, plasmonic filters are highly resilient to degradation under high power illumination. Plasmonic filters for applications in imaging, spectroscopy and telecommunications have been demonstrated by QuantIC researchers at 160nm which is a wavelength difficult to achieve for the conventional technology. Semiconductor-based photon-counting detectors have risen to prominence in the last decade as new application areas, such as quantum technology, have emerged. Silicon-based SPADs were first demonstrated in the early 1980’s, and have since come increasingly to widespread use for detecting ultra-low light levels with picosecond time resolution. Applications include LIDAR (including ground to low Earth orbit satellites), fluorescence analysis, and quantum technologies, particularly in quantum communications and quantum enhanced imaging. In the near-infrared, there are substantial

WHAT IS A SUPERCONDUCTING DETECTOR?

A superconductor is a material that, when cooled below a certain critical temperature, exhibits no electrical resistance. This behaviour can be exploited to make highly sensitive detectors of light. In one configuration the superconductor is formed into a single nano-wire that snakes back and forth forming a detector aperture. Any incoming photon is absorbed, causing the local temperature of the superconductor to rise just above the critical temperature, causing the material to no longer be superconducting. The result is a spike in the electrical resistance of the wire, and each spike signifies a photon detection. Unlike semiconductors that can only detect photons with an energy greater than the bandgap of the material, superconducting detectors can in principle work for any wavelength of material limited only by the quality of the nanowire.
issues with SPAD detectors, as their performance deteriorates at higher wavelengths due to the increased noise levels associated with the narrow bandgap semiconductors normally use. At QuantIC we are working to establish a new class of germanium-on-silicon SPADs that will operate efficiently in the near-infrared, particularly at the strategically important telecommunications wavebands at wavelengths around 1300 nm and 1550 nm. These detectors will combine the advantages of low-noise Si single-photon avalanche multiplication with the infrared sensing capability of Ge. These devices will also provide the much-needed compatibility with silicon photonics circuitry, enabling full on-chip detection in the infrared for the first time.

The project has now established a commercial source of material on 200 mm wafers (and available on up to 300 mm wafers) from IQE and full Geiger mode single photon detection has been demonstrated on this material. A new Ge passivation has been developed with one thousand fold reduction in surface trapped charge density, and limited area growth has demonstrated mesas of the required sizes for pixels without threading dislocations [F. Perzoli, et al., Appl. Phys. Lett., 2016, 108, 262103]. A material and device design without misfit dislocations in the active regions has been completed and the first material growths to test this design have been achieved.

High resolution cameras imaging the visible wavelength range are now commonplace. However, imagers in the infrared range, especially in the medium infrared range, are not yet as widely available. Cooled indium antimonide (InSb) photodiodes (PDs) are the detectors of choice for many applications in the mid-infrared region, such as gas cloud imaging, astronomical and environmental observations, and medical diagnostics. At QuantIC we are developing InSb avalanche photodetectors (APDs) providing higher speed, lower noise and superior sensitivity to enable the next generation of portable mid-infrared imagers for applications requiring high resolution and reduced weight and power consumption.

We describe the development and optical characterization of a planar medium infrared photodetector on a GaAs substrate technology, capable of integrating MESFETs, to demonstrate a new active pixel device architecture. Our results pave the way for the development of high-performance mid-IR focal plane array circuits on a single chip. Device structures with areas down to 0.0016 mm$^2$ were investigated. By deploying a silicon nitride passivation layer, we were able to reduce leakage current in reverse bias by up to 27% to yield an improved rectification efficiency. The efficiency values above unity were obtained in the near- and mid-IR wavelength range. Responsivities of up to 3.54 A/W and quantum efficiencies above unity were obtained in the near-IR range as a consequence of illumination above the bandgap causing impact ionization. In the mid-IR range, responsivities of up to 0.97 A/W were observed. The bandwidth of the devices proved compatible with video-rate standard sampling rates.

We address nonradiative recombination pathways by leveraging surface passivation and dislocation management in lm-scale arrays of Ge crystals grown on deeply patterned Si substrates. The time decay photoluminescence (PL) at cryogenic temperatures discloses carrier lifetimes approaching 45 ns in band-gap engineered Ge micro-crystals. This investigation provides compelling information about the competitive recombination between the radiative band-edge transitions and the trapping of carriers by dislocations and free surfaces. Furthermore, an in-depth analysis of the temperature dependence of the PL, combined with capacitance data and finite-difference time-domain modeling, demonstrates the effectiveness of GeO$_2$ in passivating the surface of Ge and thus in enhancing the room temperature PL.

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Quantum physics is often thought to belong to the realm of science fiction and yet it has given us the laser and semiconductor technologies that power modern day electronics and communications. QuantIC’s stakeholder engagement covers a wide variety of technical and non-technical audiences, from users of technology and industrial collaborators to the general public.

Last year saw QuantIC establishing itself as the UK Quantum Technology Hub for Quantum Enhanced Imaging with the development of its brand identity and marketing materials, and laying the foundation for its stakeholder engagement strategy. The Hub needed to engage with a wide variety of audiences at the outset from funders, government officials and industrialists to the general public and science educators. Stakeholders have been prioritised and activities reviewed to focus on the following objectives of the UK National Quantum Technology strategy:

- Stimulating applications and market opportunities;
- Creating a strong foundation of capability;
- Growing a skilled UK workforce.

QuantIC’s marketing has evolved this year to centre around case studies of industrial collaboration supporting the development of marketable technology. The Hub making its first foray into exhibiting at international events such as SPIE Security and Defence.

QuantIC strengthened its relationship with the Scottish Schools Education Research Centre (SSERC) and also sponsored a quantum summer school at the University of Bristol. The Hub’s permanent exhibition on quantum technologies at the Glasgow Science Centre was also launched this year as a platform for ongoing public engagement. These are just some of the marketing and stakeholder engagement highlights and the following pages provide more information on these and other high points in another busy year for QuantIC.

WHO ARE THE QUANTUM BUDDIES?
The Quantum Buddies is a pilot public engagement project that was initiated in early 2016 by QuantIC.

The aim of the project is to pair up Physics teachers with a “buddy”, a physicist or engineer with insight into Quantum Physics, to help support in the teaching of the subject.

The project has initially focused on developing a bank of learning resources that were pulled together by a group of academics, PhD students and retired Physics teachers.

QuantIC is now partnering with Science Connects to offer support from Quantum Buddies to secondary schools across the West of Scotland via the STEM Ambassador Network.

More information and downloadable resources can be found here:

https://quantic.ac.uk/quantumbuddies/

RESPONSIBLE RESEARCH AND INNOVATION
QuantIC is already embedding the Responsible Research and Innovation (RRI) dialogue in the way it is working with industry to develop its technology applications in response to market needs. It has also taken a similar strategy with its public and stakeholder engagement activities. Using the tagline, “What would you do with a camera that can…?” QuantIC’s messaging approach invites the audience to explore the applications of quantum imaging technologies and to start a dialogue with the Hub’s researchers on what is possible. This approach also sidesteps explaining the definition of quantum science at the outset where there is a lack of awareness and understanding as highlighted by a BIS funded Sciencewise report.

QuantIC developed marketing materials in support of its public and stakeholder engagement strategy. An animated film was created highlighting some of the Hub’s research in a friendly, non-technical manner and this has been placed on the QuantIC website and screened at public and stakeholder events (https://quantic.ac.uk/innovation/resources/).

The animated QuantIC film was also complemented by a brochure that can be distributed online and at events. The Hub also secured editorials in International Innovation and Adjacent Government journals with readerships consisting of government, policy makers and academics in the UK and European Union.

Looking ahead, QuantIC has also started a YouTube channel and will be looking to develop filmed content and use this as a platform for promoting its technologies (https://www.youtube.com/channel/UCP5pH4VFL.iI7J014J6c55/g).
A workshop on quantum enhanced imaging for the defence and security sector was organised by QuantIC in partnership with one of the world’s leading defence technology and security companies, QinetiQ. Hosted at QinetiQ’s Malvern premises, the event was attended by over 25 industrialists from organisations such as Airbus, Dstl, BAE Systems, e2v, Leonardo and Thales UK.

The workshop was opened by QinetiQ’s Chief Technology Officer, Jeremy Ward who gave a brief overview of the imaging challenges facing the sector. This was followed by an overview of QuantIC by Professor Miles Padgett, the Hub’s Principal Investigator, and an invited talk by Simon Bennett, Deputy Director of Strategy and Planning at Innovate UK, who spoke about the investment the UK government has made in quantum technologies and the opportunity this presents industry with. Technology poster sessions and round table discussions on topics such as seeing through a brownout and imaging with sparse data allowed industrialists to explore possible applications with the Hub’s researchers.

Jeremy Ward, Chief Technology Officer of QinetiQ, said: “Quantum imaging can be useful for imaging in low-light or brown-out conditions or seeing round corners. We’re glad to have been involved in sponsoring the workshop to explore mutual areas of collaboration within the sector and with QuantIC.”

QuantIC Principal Investigator, Professor Miles Padgett, added: “We’re grateful to QinetiQ for sponsoring the workshop with us. It’s allowed us to improve our understanding of the industrial challenges facing the defence and security sector and to build our contact base with industry.”

As a direct result of the event, a joint PhD studentship was funded between QuantIC and QinetiQ and a follow up workshop with Dstl was organised. We have also built upon our existing collaborations with Leonardo and Thales UK approving two new partnership resource projects on mosaic filters and InAs detectors.
How can quantum physics be used in a zombie apocalypse? QuantiC researchers collaborated with actors and artists to devise an immersive theatrical event, “Agent Photon and the Quest for Quantum”, to engage school pupils and the public on their research at the Glasgow Science Festival this year.

Held in a secret location at the University of Glasgow, the secondary school pupils and public who came along were met by “Professor Heisenberg” who told them that they were being inducted into the Heisenberg Quantum Academy. However the induction didn’t last long as “Agent Photon” arrived seeking help with the outbreak of a zombie apocalypse. What followed was a race against time for everyone to work in teams with QuantiC researchers to find out more about quantum physics and the Hub’s research to build gadgets to save the world.

The event was very well received, with 98% of attendees indicating that it had helped them to learn something about quantum physics and QuantiC research. Participants enjoyed the interaction of building gadgets and “having to think about potential applications of quantum technology”. One teacher commented, “it is great that the pupils have a chance to design their own gadgets and apply what they learn, as well as relate applications to theory”.

The practical elements of the event were also complemented by a quantum physics lecture, which reinforced some of the science underpinning the experiments that were demonstrated. The session, targeted to the secondary school pupils, also featured a talk by Dr Craig Hamilton from M Squared Lasers. Dr Hamilton shared with the audience his experience working as an engineer and entrepreneur at the interface between academic research and industry.

Based on the feedback we received, participant most enjoyed building gadgets. Respondents to the survey also asked for more zombies, giving us food for thought for the planning of the next apocalypse.
QuantIC was pleased to support the QETLabs Quantum in the Summer school organised by the Quantum Engineering Technology Labs (QETLabs) at the University of Bristol. Sixteen students between 16-22 years of age from around the UK attended the week long intensive summer school which ran from 25 – 29 July 2016.

"Quantum in Summer", which celebrates light in all its forms, was developed by Mr Javier Sabines, PhD student at QETLabs and QuantIC researcher at the University of Bristol. The schedule covered a wide range of topics from Young’s double slit experiment and the photoelectric effect to quantum information and quantum key distribution. Lectures were interspersed with lab experiments and tours to learn about research at the University. Most of the topics had been covered in the syllabus for A Levels and the programme was designed to give students an insight into studying physics and engineering at the university level. In addition to this, the instructors of the summer school shared their personal experiences as scientists, providing useful tips for successful research and making the students aware of the potential career options available with a scientific degree.

Feedback was very positive and many would recommend it to other students. Amy Clayton, from Chatham and Clarendon Grammar School, said: “The summer school has made me see how useful scientific research can be and it’s made me more inclined to pursue a career in academia. I also found it thoroughly interesting hearing about the latest discoveries and advances and I’m intrigued to read more about current scientific research.” Micha Lanez, from Kingswood School in Bath, added: “I learnt about many new applications of optics such as in quantum computing, communications and measurements. I never knew about most of these before the course.”

It was also encouraging to find that attendees were inspired to share their learning. George Oxley, from Churchill Academy and Sixth Form, said: “There is a STEM club at school which is aimed at younger years and is run by sixth formers. Next year I will be hoping to play a bigger part in this.”

Given the success of last year’s event, QuantIC has already committed to support the QETLabs “Quantum in the Summer” 2017 edition taking place in Bristol from the 7-11 of August 2017.
QUANTIC EXHIBITS AT SPIE SECURITY AND DEFENCE 2016

26-29 September 2016, Edinburgh International Conference Centre, Edinburgh

With QuantIC technology gaining increasing traction with industry partners, the Hub took its first step towards exhibiting at a well-known trade event, to raise its profile and facilitate more partnership opportunities.

SPIE Security and Defence is a leading conference and exhibition that brings together business leaders, scientists and engineers from some of the world’s foremost research organisations and companies in the photonics sector. This year, nearly 1000 participants and 41 exhibitors attended the annual event in Edinburgh.

On display were two technology demonstrators never before exhibited by the Hub: the “Low-cost 3D Imaging System” and the “Hidden Object Tracker”. The low cost 3D camera has been developed in collaboration with Leonardo. The system is based on a single-pixel camera and exploits its exquisite timing resolution to offer real advantages in 3D ranging applications.

The Hidden Object Tracker, developed in collaboration with Thales UK, showcased a camera system that, as the name suggests, can image and track objects hidden behind a corner. The Hub’s exhibition stand was busy and saw interest from companies such as BAE Systems, Airbus Defence and Space and Raptor Photonics.

Quantum technology was also in the spotlight this year, with Sir Peter Knight featuring as a plenary speaker presenting on the “Second Quantum Revolution” and UK National Quantum Technologies Programme. QuantIC was also represented in the conference proceedings with Professors Gerald Buller and Robert Hadfield giving keynote talks on their research. Moreover, PhD student Aurora Maccarone from Prof Gerald Buller Group, won Best Student Paper for “Depth imaging in highly scattering underwater environments using time-correlated single photon counting”.

Photo: The QuantIC stand at SPIE Security and Defence 2016.
Building on the success of the inaugural UK National Quantum Technologies Showcase held in 2015 at the Royal Society, the 2016 National Quantum Technologies Showcase was moved to a bigger venue – the Queen Elizabeth Conference Centre. The exhibition was expanded with a three-fold increase in the number of exhibits. Demonstrators on display were contributed by both academia and industry and showcased technological development and innovation across a range of sectors.

QuantIC’s success in the programme was evident with the Hub fielding the largest number of exhibits from a single organisation. What was also significant was that most of QuantIC technologies were jointly exhibited with industry partners highlighting the market traction already achieved by the Hub. This included “Gas-Sight” with M Squared Lasers, “Low Cost 3D Imaging” with Leonardo, “Wee-g” with Bridgeporth, “Multiplexed Single-Photon Timing Fluorescence” with Horiba Jobin Yvon, “Miniaturised components” with Lockheed Martin UK, “Sensing Single Light Quanta” with Rutherford Appleton Laboratory “Highly efficient photon pair for low noise imaging”, “covert range finding”, “Hidden Object Tracker” with Thales and “Automated Video Surveillance” with Aralia Systems.

Key highlights from this year’s showcase included the launch of the Blackett Review on Quantum Technologies by the Government Office for Science and the announcement of the winners of Innovate UK’s Quantum Technologies Innovation Fund. The event clearly highlighted the programme’s potential for economic impact in the UK and helped strengthen the case for further investment.

Over 600 people registered for the 2016 National Quantum Technologies Showcase with almost 50% of attendees coming from industry and government. Feedback from participants was positive, with almost all respondents from the survey indicating that the event had improved their understanding of the UK National Quantum Technologies Programme. The general consensus amongst participants was that the event had played a major role in showcasing the scale of the activity and opportunity presented by quantum technologies in the UK.

2016 NATIONAL QUANTUM TECHNOLOGIES SHOWCASE
3 November 2016, Queen Elizabeth Conference Centre, London
Keith Brown MSP, the Scottish Government’s Cabinet Secretary for Economy, Jobs and Fair Work, officially opened the QuantIC Innovation Space during his visit to the University of Glasgow on 23 November 2016.

Mr Brown was given a tour of the space and was shown some of QuantIC’s collaborative projects, which were jointly exhibited by the Hub’s researchers and industry partners. The 200 square-meter Innovation Space, which was made a reality with support from the Scottish Funding Council (SFC), was purpose-built to make it as easy as possible for QuantIC researchers to work with industry partners and offers custom laboratory and office space on flexible schedules.

Mr Brown said: “I am delighted to launch the QuantIC Innovation Space, which will create a place and space for companies to connect at an early stage with researchers to collaborate and innovate on projects related to imaging technology. A thriving economy is only made possible by having a business base which is willing and able to innovate. I wish all the university and business partners involved in QuantIC every success in driving forward research, increasing innovation and growing Scotland’s economy.”

John Kemp, interim chief executive of the SFC, added: “This innovative addition to Scotland’s research base is already making productive connections with the pioneering quantum technology industry, SFC is delighted to support this exciting innovation space and I look forward to seeing more companies benefit from collaborations with QuantIC researchers.”

Professor Miles Padgett, QuantIC principal investigator, stated: “Less than two years since it was officially launched with an event at the Glasgow Science Centre, QuantIC has made strong progress both commercially and academically. We have forged relationships with more than 70 companies, published close to 60 research papers, and raised an additional £9.2M to support research and exploitation activities. The UK is home to some of the world’s best quantum imaging researchers and we are proud that QuantIC is helping to commercialise their work for the benefit of the UK economy.”

Companies that are already making use the QuantIC Innovation Space include M Squared Lasers, Bridgepoth and Chromacity.
Complementing QuantIC’s strategy of accelerating technology uptake with industry, the Hub has been active in engaging other stakeholders such as the public, government and educational bodies. A key highlight of this has been the development of a permanent exhibition in collaboration with the Glasgow Science Centre to raise awareness and educate the public about its research and quantum physics more generally. QuantIC scientists worked closely with the team at the Glasgow Science Centre to ensure that the complex science was understandable and to help explain how it was relevant to everyday lives.

Dr Stephen Breslin, Chief Executive of the Glasgow Science Centre, has been very supportive of the collaboration with the Hub: “We are very excited to be amongst the first to be able to bring this technology to the public and hope the exhibition will inspire a new wave of quantum physicists to help take forward this cutting edge work to discover the field’s full potential for the benefit of mankind.”

Examples of QuantIC research underpinning the exhibits include “Light in Flight”, “Single Pixel Camera” and “Mid-Infrared and Terahertz imaging”. Visitors also get a chance to learn more about quantum theory such as Young’s double slit experiment, light’s properties and what it’s like working in an optics laboratory.

Launched on 29 April 2016, the “Making the Invisible Visible” exhibition by QuantIC at the Glasgow Science Centre has been seen by 155,193 public visitors and 31,638 education visitors. A survey conducted in December 2016 found that over 70% of visitors had rated the exhibition “excellent” or “good” and had appreciated the variety of displays which appeal to different age groups.

It is hoped that the interactive exhibits featuring QuantIC research will start the public conversation about new applications for quantum technology. Plans are in place to use the exhibition as a platform for “Meet the Experts” sessions with the Hub’s researchers to further the dialogue and innovate responsibly.

MAKING THE INVISIBLE VISIBLE
29 April 2016, Glasgow Science Centre, Glasgow
QUANTIC MANAGEMENT BOARD

The QuantIC Management Board has overall responsibility for the delivery of the programme, including monitoring technical and commercial progress and ensuring the project meets its objectives. The board membership is detailed below:

• Steve Beaumont, Director and Chair of QuantIC Management Board
• David Cumming, WP4 leader
• Martin Dawson, rep for University of Strathclyde
• Sara Diegoli, QuantIC Programme Manager
• Animesh Datta, QuantIC Programme Manager
• Ian Walmsley, rep for University of Oxford.
• Alastair Wilson, Chair of the Market Opportunities Panel

QUANTIC MARKET OPPORTUNITIES PANEL

A key feature of QuantIC is the role industry plays in directing the spend of our £4M Partnership Resource Fund (PRF) and in helping to set the overall direction of the technology development programme. Our Market Opportunities Panel (MOP) reviews each PRF application and makes a recommendation for funding, which is then ratified by our Management Board.

The MOP’s active support and commitment to QuantIC has been invaluable; individual members have facilitated introductions and supported collaborative ventures. The panel also advises the Hub on management and exploitation of intellectual property and on internationalisation.

The members of the QuantIC Market Opportunities Panel are listed below:

• Alastair Wilson, Chair of the MOP
• William Alexander, Thales UK
• John Bagshaw, independent consultant
• Simon Bennett, Innovate UK
• Colin Coats / Colin Duncan, ANIDOR, an Oxford Instruments Company
• Trevor Cross, e2v
• Tony Espie, BP Group Technology
• Robin Hart, NPL
• Robert Lamb, Leonardo
• Anke Lohmann, KTN
• Graeme Malcolm, M Squared Lasers
• Andrew Middleton, Dstl
• Eleanor Mitchell, Scottish Enterprise
• Andrew Smout, Toshiba Medical Visualisation Systems
• Bruce Rae, STMicroelectronics
• Andy Smout, Toshiba Medical Visualisation Systems
• Alastair Wilson, Chair of the MOP
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• Eleanor Mitchell, Scottish Enterprise
• Andrew Smout, Toshiba Medical Visualisation Systems
• Bruce Rae, STMicroelectronics
• Andy Smout, Toshiba Medical Visualisation Systems

QUANTIC STRATEGIC ADVISORY BOARD

The QuantIC Strategic Advisory Board (SAB) has international membership spanning academia and industry. The SAB advises the QuantIC Management Board on the overall strategic framework of the Hub, monitors our governance and makes recommendations on topics including research, technological development and commercial exploitation. The board membership and affiliation are detailed below:

• Elisabeth Giacobino, (Chair of QuantIC SAB) Directeur de recherche Emerite, CNRS
• John Bagshaw, Independent Technology Consultant and former Technology Executive at BAE Systems
• Jonathan Flint, Independent SAB member and former Chief Executive at Oxford Instruments
• Dan Gauthier, Duke University
• Animesh Datta, EPSRC
• Peter Knight, Imperial College London.

QUANTIC SCIENTIFIC MEETINGS

QuantIC organises quarterly scientific meetings to bring the Hub’s research community together. Research Associates directly funded by QuantIC as well as students and researchers with aligned interests that are funded from other sources gather for networking and scientific discussions.

External speakers are also invited to the meetings to offer an overview of related technologies and developments that are of interest to the programme.

QUANTIC YEAR TWO REVIEW

In 2016, QuantIC completed a Year Two Review. The aim of the review was to provide a quantifiable snapshot of the QuantIC technology development programme. QuantIC followed a rigorous process in which industry was given a central role in assessing our technology against technical progress, competitiveness and routes to exploitation.

By assessing technical progress, competitive advantage and user engagement after only 20 months of work, we intentionally set a high bar for the justification of continued funding of each of our demonstrators and for any new opportunities identified in the first phase. These results are now being used to maximise the success and sustainability of the Hub.

Our strategy following this review is to accelerate the most promising demonstrators, identify additional funding to support their exploitation in the final years of the programme, and support technology that is in demand but not yet mature. We will continue to hold light-touch reviews annually for the duration of the project in addition to the quarterly progress reporting which already features in our project management system.

In its second year, QuantIC has expanded its programme to respond to the needs of our industry partners. Our ability to adapt is largely due to our governance structure, which brings industrial and international expert input to the flexible application of resources and strategic direction.
Publication list


APPENDICES

QUANTIC CO-INVESTIGATORS

• Miles Padgett FRS, FRSE is QuantIC’s Principal Investigator and WPI leader. He holds the Kelvin Chair of Natural Philosophy at the University of Glasgow.
• Steve Beaumont, FREng is QuantIC Director and Vice Principal Emeritus at the University of Glasgow.
• Stephen Barnett FRS, FRSE is Professor of Quantum Theory at the University of Glasgow.
• Adrian Bowman FRSE is Head of the School of Mathematics and Statistics at the University of Glasgow.
• Gerald Buller FRSE is Professor of Physics at the University of Heriot-Watt and EPSRC Established Career Fellow in Quantum Technology.
• David Cumming FRSE is WP4 leader, Professor of Electronic Systems and Head of the School of Engineering at the University of Glasgow.
• Animesh Datta is Assistant Professor in Theoretical Physics at the University of Warwick and EPSRC Early Career Fellow.
• Martin Dawson FRSE is both Director of Research at Strathclyde’s Institute of Photonics and inaugural Head of the UK’s first Fraunhofer Centre for Applied Photonics, CAP.
• Daniele Facio FRSE is WP2 leader and Professor of Physics at the University of Heriot-Watt.
• Erdan Gu is an Associate Director and Research Team Leader at the Institute of Photonics, University of Strathclyde.
• Robert Hadfield is Professor of Photonics at the University of Glasgow and Head of the Electronic and Nanoscale Engineering division.
• Giles Hammond is Professor of Experimental Gravitational Physics at the Institute of Gravitational Research at the University of Glasgow.
• Robert Henderson is Professor at the Joint Research Institute for Integrated Systems in the School of Engineering and Electronics at the University of Edinburgh.
• Stefan Hild is a Professor of Experimental Physics at the Institute for Gravitational Research at the University of Glasgow.
• Jim Hough FRS FRSE is Research Professor in Natural Philosophy in the School of Physics and Astronomy at the University of Glasgow.
• Jonathan Leach is Assistant Professor in the School of Engineering & Physical Sciences at the University of Heriot-Watt.
• Jonathan Matthews is Lecturer in Quantum Photonics at the University of Bristol and EPSRC Early Career Fellow.
• Roderick Murray-Smith is a Professor of Computing Science at the University of Glasgow.
• Douglas Paul FRSE is the Professor of Electronic and Nanoscale Engineering EPSRC Research Fellow.
• Sheila Rowan FRSE is Director of the Institute for Gravitational Research at the University of Glasgow.
• John G Rarity FRS is Professor of Optical Communications Systems at the University of Bristol.
• Michael Strain is a lecturer in Photonic Semiconductor Devices at the Institute of Photonics, based at the University of Strathclyde.
• Ian Walmsley FRS is Pro-Vice Chancellor (Research and Innovation) and Hoole Professor of Experimental Physics at the University of Oxford.
• Matthew Walters is a Professor of Clinical Pharmacology at the Institute of Cardiovascular and Medical Sciences at the University of Glasgow.
• Ian Watson is Research Team Leader at the Institute of Photonics, based at the University of Strathclyde.


Quantum technology challenges for the 21st century, Chicheley UK (Invited).


May 2016: M. J. Padgett, Orbital Angular Momentum in Optical Fibre Communications, Royal Society, UK (Invited).

May 2016: M. J. Padgett, Quantum Technologies for the 21st Century, Royal Society, UK (Invited).


July 2016: J. Rarity “Photonic quantum information,” IMEC Summer School, Bristol, UK (Invited).


July 2016: R. Henderson “100 Mb/s wavelength division multiplexing visible light communications link using a triple-junction photo-diode,” IEEE Photonics Society Summer Topical Meeting, Newport Beach, USA (Invited).


July 2016: G. Hammond “MEMS: from shadows to interferometers,” EIT ISM conference on optics and microfluidics, Glasgow, UK.


August 2016: A. Datta “Quantum limits to sensing and imaging,” BBN Technologies (Raytheon), Cambridge, USA.


September 2016: M. Agnew “Entanglement swapping of orbital...
Angular momentum states,” IDP Photon 16, Leeds, UK.


October 2016: V. Datta, Pioneers in Quantum Optics and Quantum Information Science: Celebration of the Academic Life of Carlton M. Caves, Albuquerque, NM, USA.


October 2016: M. J. Padgett, Frontiers in Optics, OSA-100th Anniversary, Rochester, USA.


November 2016: J. Herrnsdorf, M. J. Strain and M. D. Dawson “Control of automated systems with a structured light illumination source,” Photonics Conference (IPC), Hawaii, USA.

October 2016: W. Roga “Security against jamming and noise exclusion in imaging.” 3rd UK-Japan Quantum Technology Workshop, Tokyo, Japan (Invited).


October 2016: A. Datta, Pioneers in Quantum Optics and Quantum Information Science: Celebration of the Academic Life of Carlton M. Caves, Albuquerque, NM, USA.


Public Engagement

D. Faccio - Published video on “imaging hidden objects” in December 2015.

M. Dawson, I. Watson and E. Gu – Connected Nation: Thriving in a Digital World (EPSRC), British Library, 8th December 2015.

M. J. Padgett, R. Aspden and P. Chua – Quantum Physics Teachers Workshop with Scottish Schools Education Research Centre (SSERC) at Sathosphere Science Centre, Aberdeen in March 2016.


J. Leach – Quantum Physics Lecture at the Institute of Physics Teachers’ meeting, Edinburgh in March 2016.

M. Edgar, G. Gariepy, R. Aspden, R. Warburton and P. Chua - Development of “Making the Invisible Visible” permanent exhibition at Glasgow Science Centre which launched in April 2016.

ORGANISED: April 2016 - joint QinetiQ and QuantIC workshop.

J. Herrnsdorf - exhibited “Micro-LED array positioning” at Scottish Universities Physics Alliance (SUPA) Annual Gathering, Glasgow in May 2016.

QuantIC – “Electron Diffraction Tube” and “Quantum Tunneling in Radioactive Decay” teaching resource films
Innovate UK Quantum Briefing event in

- workshop for QuantIC scientists in July 2016.
- ’Mirrors, chirality and Stegosaurus” – R. Cameron (Talk)
- “Woe-g in a lift” – R. Middlemiss


- Doug Paul authored the Institute of Physics President’s Medal 2015.
- Ian Walsmsley appointed to the European Commission High-Level Steering Group for the Quantum Flagship.
- Stefan Hild awarded the 2015 winner of the Royal Society of Edinburgh/Sir Thomas MacDougal Brisbane Medal.
- Miles Padgett awarded the 2015 Prize for Research into the Science of Light by the European Physical Society.

- Gerald Buller was Elected Fellow of Optical Society of America in the 2017 Class “for pioneering work in single-photon detection and applications of single-photon technology in three-dimensional imaging and quantum communications”.
- Robert Hadfield was Elected Fellow of the Optical Society of America in the 2017 Class “for pioneering contributions in the development of infrared superconducting single-photon detectors and advanced photon-counting applications”.

- Martin Dawson awarded 2016 Aron Kressel Award of the IEEE Photonics Society “For broad and sustained contributions to semiconductor optoelectronic engineering, including optically pumped semiconductor lasers, diamond photonics and gallium-nitride microdevices”.

- Martin Dawson awarded Denis Gabor Medal “for his vision and leadership in applied photonics, including pioneering contributions to optically pumped semiconductor lasers, diamond photonics and gallium nitride optical microsystems, and for fostering the international development and commercialisation of these technologies.”

- Sheila Rowan awarded WIRED Audi Innovation Awards: Scientific Breakthrough because she “played a vital role in the design and construction of the fused silicon suspension systems for the LIGO mirrors” and for “leading the huge effort which won our Scientific Breakthrough award.”

- Rebecca Douglas, Giles Hammond, Stefan Hild, James Hough, Sheila Rowan, Steven Bramslepie and Richard Middlemiss awarded the IQP Breakthrough Prize.

QuantIC - “Creative Collaborations” workshop for QuantIC scientists in July 2016.

- J. Sabin-costering and J. Matthews - Quantum Photonics Summer School, Bristol, supported by QuantIC in July 2016.

Organised: QuantIC hosted an Innovation UK Quantum Briefing event in July 2016.

QuantIC - “Imaging the future with QuantIC” film produced in August 2016.

- Exploration: September 2016 - QuantIC exhibited:
  - “Creative Cameras” – D. Philips, R. Hay, Toninelli.
  - “Seeing the invisible in the mid-infrared” – P. Vusinio
  - “Mirrors, chirality and Stegosaurus” – R. Cameron (Talk)
  - “Woe-g in a lift” – R. Middlemiss

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- “Imaging through obscurants using single-photon and few-photon detection in the short wave infrared” (£79,031) Gerald Buller, October 2016: dstl.

KNOWLEDGE EXCHANGE AND INNOVATION FUNDING

Royal Society Discussion Meeting on Quantum Technologies (£5k), Ian Walsmsley, May 9 -11, 2016.

- Ian Walsmsley, Martin Dawson and Endan Gu provided a submission for Connected Nation: Thriving in a Digital World

Funding

RESEARCH FUNDING


Poster Prize: Nature Publishing Group (£1K), Ian Walsmsley, Springer.

Institutional support through University of Bristol to develop methane LIDAR using photon counting technology (£25K), John Rarity, EPSRC.

Royal Society Research Professorship (£60k), Stephen Barnett.

“Deterministic photonic entanglement using time-frequency control” (£120k) I. Walsmsley, AFOSR (US Air Force Office of Scientific Research): FA9550-17-1-0064 DEF.

“Compact Multispectral Imager for Nanosatellites” (£75k), Daniel Ol, David McKee and John Jeffers, December 2016: UK Space Agency, National Space Technology Programme Path Finder Grant.

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• The Conversation: http://theconversation.com/the-amazing-camera-that-can-see-around-corners-51948.  
• CNN Expansion (Spanish): http://expansion.mx/tecnologia/2015/12/07/esconderte-de-la-foto-con-esta-camara-ya-no-sera- posible.  
• BBC World Service 31 March 2016 22:50:26 Researchers at the University of Glasgow in the UK have used accelerometer technology to build new gravimeters.  
• BBC Radio Berkshire 31 March 2016 16:42:12 An invited audience at the University of Glasgow has built a sensor the size of a postage stamp that can detect tiny fluctuations in the earth’s gravitational pull, which could eventually be used to warn of an impending volcanic eruption.  

A number of web and press features were also written about the MEMS gravimeter publication:  
• The Engineer: http://www.theengineer.co.uk/smartphone-mems-adapted-to-create-affordable-gravimeters/  

Other Media Coverage  
• A profile of QuantIC was featured in the Adjacent Government journal which “produces compelling and informative products for a wide audience.”  
• QuantIC was profiled in International Innovation Journal in July 2016.
PARTNERS: QuantIC is a collaboration between the Universities of Glasgow, Bristol, Edinburgh, Heriot-Watt, Oxford, Strathclyde and Warwick.

FUNDING: QuantIC is the UK Quantum Technology Hub in Quantum Enhanced Imaging. The project is supported by the EPSRC UK Quantum Technologies Programme under grant EP/M01326X/1. Additional funding was also provided by the Scottish Funding Council under grant H14051.
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The UK Quantum Technology Hub in Quantum Enhanced Imaging

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