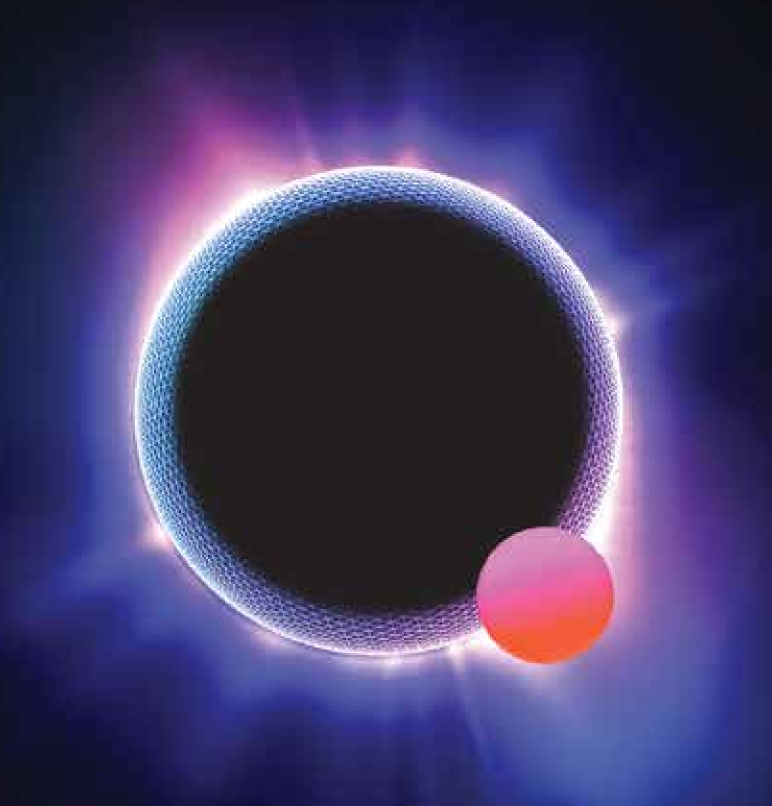
Army

Army Quantum Technology Roadmap

April 2021



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Foreword

As highlighted in *Accelerated Warfare, Army in Motion* and the *Army Objective Force*; harnessing emerging technology is key to gaining and retaining military advantage in the future. Australian Defence strategic guidance in the *2020 Defence Strategic Update, 2020 Force Structure Plan,* and *More, Together: Defence Science & Technology Strategy 2030* all highlight the value of quantum technology. Quantum technologies have been identified as having substantial disruptive potential across a range of military applications for the future Joint Force. They offer significant military advantage to early adopters especially in the field of communication, navigation, computational power and high precision sensing as well as simulation, encryption and artificial intelligence.

To ensure Army is able to secure such advantage, this Roadmap provides the framework for the exploration and exploitation of this range of technologies. As part of being *Future Ready*, Army needs to consider and explore the opportunities that quantum technology offer. Australia currently has a unique position in the quantum technology ecosystem and Army must seize the opportunity this presents as part of the future Joint Force.

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Head Land Capability
April 2021

Executive Summary

Quantum technologies are a suite of emerging technologies that exploit the fundamental laws of nature to offer unprecedented capabilities in sensing, imaging, communications and computing. They are diverse, complex, generally early in technical readiness and demand new ways of thinking about the employment and exploitation of technology. Their true capabilities, limitations, most disruptive applications and associated counter-measures are still being discovered.

This combination of disruptive potential, ambiguity and complexity presents both strategic risks and opportunities to Land Forces. As a result, Army finds itself in an accelerating global competition to understand, co-develop and exploit quantum technologies for land operations.

This Roadmap seeks to frame and present Army's approach to quantum technology in order to deliver Army a quantum advantage in land operations.

Three key points frame Army's approach:

- Australia is faced with the strategic challenge of converting its global leadership in quantum technology research into sustainable industrial and defence advantage.
- Defence has a role in aligning extant research and development (R&D) capacity to Defence's priority problems. This includes shaping and guiding these technologies as they develop to facilitate transition of technology concepts into capability for the warfighter.
- In alignment with the strategic themes of adaptive thinking, partnering, sovereign industry and integration in *Army in Motion and Accelerated Warfare*, Army's Roadmap will explore the potential use of quantum technologies for the land domain.

To develop Army's quantum technology capability, Army will pursue four objectives:

1. **Establish.** Rapidly establish a quantum innovation ecosystem focussed on land domain opportunities.
2. **Identify.** Identify the most disruptive and advantageous applications of quantum technologies for the land domain.
3. **Develop.** Develop the related technology, operating concepts and modified force designs.
4. **Support.** Support Defence's quantum technology strategy development.

To achieve the four objectives, four interacting lines of effort will be undertaken.

Collaborate	Growth of an Army Chapter of a Defence Quantum Innovation Community. Deep collaboration with the Chapter will allow for the convergence of ideas on the applications of quantum technologies, shared situational awareness of developing technologies, mapping of capabilities and supply chains, and the support of quantum education across Army, Defence and the defence industry.
Explore	Implementation of a rapid quantum application discovery and testing cycle via regular Army Quantum Technology Challenges (the Challenges). The Challenges will seek to identify the most promising applications of quantum technology, prior to the commitment of Army resourcing. These Challenges will take a portfolio approach that balances technical risk with potential application value over the different types of quantum technology.
Exploit	Focussed development of quantum technologies, operating concepts and force designs that will inform Army on how to best exploit quantum technologies to enhance existing capabilities and operations and to gain new capabilities and ways of operating. Army will seek to support inventors beyond the demonstration of operating concepts to enable them to continue to develop their technology and prepare for subsequent progress through the Capability Life Cycle. This development and the Challenges may be supported by newly established simulation and testing facilities.
Refine	Continuous curation of Army's quantum technology understanding, landscaping, assessment and strategy.

End state

The conditions are set for Army to gain and retain an early quantum advantage in the Land domain.

This condition is marked by an engaged innovation ecosystem focussed on developing applications for land operations, identification of high-value applications of quantum technologies, the associated technologies, operating concepts and force designs under development, and a refined Army understanding and approach to quantum technology.

This Roadmap will be updated as quantum technologies, the global and domestic landscapes and Army's understanding and approach evolves.

Introduction

Quantum technologies exploit the fundamental laws of nature to reach the ultimate limits of sensing, imaging, communications and computing, and thus promise otherwise impossible capabilities. They are no longer scientific speculation; substantial public and private investments around the world are accelerating their development and application. This acceleration will likely see quantum technologies transform defence, science and industry over the next 20 years; particularly when combined with other emerging technologies, such as nanotechnology, biotechnology, space technology, artificial intelligence (AI) and robotics. Yet precisely when and how quantum technologies will transform Defence is not clear.[1]

The diversity and complexity of quantum technologies demand new ways of thinking about the employment and exploitation of this technology. Their true capabilities, limitations and most disruptive applications are still being discovered, which presents both strategic risks and opportunities to Army.

There is in an intensifying global competition to understand, co-develop and exploit quantum technologies for the land domain. Through wide engagement and a continually agile and collaborative approach, Army can gain and retain a quantum advantage by leveraging Australia's national strategic strength in quantum technology research, its emerging quantum industry and cooperation with aligned nations.

The purpose of this Roadmap is to frame and define Army's approach to quantum technology to catalyse the development and application of quantum technologies for the land domain. The core of this innovation ecosystem being drawn from Army, broader Defence and Australia's quantum technology research community and industry.

This Roadmap is designed to fit within, complement and inform emerging national and Defence quantum technology policies and initiatives. It does not contain technical details of quantum technologies, which are best found elsewhere.[2]

Quantum Technologies

Quantum technology is a term that encompasses a diverse suite of technologies. These technologies are at different levels of readiness and have different development timelines. Their defence applications are rapidly evolving and expanding, with many yet to be discovered.

The aim of this section is to introduce the key information required to navigate quantum technologies and to begin identifying and assessing their defence applications. Further information and discussion can be found in the annex.

Definition

A quantum technology is one whose functionality derives from engineering the states of individual quantum systems. This distinguishes quantum technologies from earlier 20th century technologies (for example, lasers, magnetic resonance imaging, semiconductor electronics) that employ quantum phenomena (for example, coherence, quantised energy, tunnelling), but do not directly initialise, manipulate and measure the states of individual quantum systems.

The simplest quantum system is the ***qubit***, which forms the fundamental building block of most quantum technologies (others employ continuous variables of quantum systems). The qubit is a useful abstract concept that allows us to understand how different quantum technologies work and compare. In practice, different systems of particles or different variables of similar systems fulfil the role of the qubit in different technologies.

Characteristics

Quantum technologies function by using normal 'classical' devices (for example, lasers, microwave electronics and photodetectors) to initialise (for example, by a laser pulse), manipulate (for example, by a microwave pulse) and measure (for example, by detecting emitted photons) the state of their qubit(s).

A classical computer is used to program and control these devices and record the measurement data. Thus, quantum technologies are generally operated using a familiar interface.

Despite qubits being a relatively small component of the quantum technology, their different physical behaviour is what delivers advantage over classical methods.

Types

Quantum technologies can be broadly categorised into three main types:

- **Quantum sensing and imaging.** Enabling improved limits in precision, stability and accuracy.
- **Quantum communications and cryptography.** Networking quantum devices and enabling physically-assured security.
- **Quantum computing.** A leap in computational power for certain tasks.

Quantum technologies are enabled by a variety of high-performance classical technologies, advanced fabrication and testing facilities and skilled workforces. There are also a variety of possible countermeasures to quantum technologies. They range from methods of disrupting quantum communications to post-quantum encryption protocols that secure information against decryption by quantum computers.

Timelines

The current development states and projected future development timelines of technologies within each type are summarised in table 1.

Current development state	In production/advanced stages of industry R&D	Intermediate industry R&D/advanced stages of academic research	Early stages of industry R&D intermediate stages of academic research
Estimated time to defence application	**<5 years**	**5-10 years**	**>10 years**
Sensing and imaging	• Quantum accelerometers magnetometers, gyroscopes and clocks • Quantum microscopes	• Quantum spectrometers and detectors • Chip-scale bio/ chemical analysers • Quantum-enhanced Magnetic Resonance Imaging	• Wearable magnetoencephalography • Quantum nanosensors for biomedicine
Communications and cryptography	• Simple short-range Quantum Key Distribution networks	• Quantum repeaters • Quantum ports • Complex long-range • Quantum Key Distribution networks • Synchronisation of clocks	• Quantum memories • Networks of quantum sensors and computers
Computing and simulation	• Mainframe Noisy Intermediate-Scale Quantum computers	• Distributed and edge Noisy Intermediate-Scale Quantum computers intergrated in classical networks • Error-corrected mainframe computers	• Large-scale Error-corrected mainframe computers capable of cryptography • Distributed error-corrected computers in quantum networks

Table 1: Current state and projected development timelines of different quantum technologies.

Assessment

Assessment of quantum technologies for the Land domain requires consideration of:

- The dimensions of development risk, time to application and potential advantage.
- The diversity and early stage of quantum technology where precise judgement of the above dimensions are not possible and that many applications are yet to be discovered.

- The current and future contexts and requirements of land operations, and how they may be modified by quantum technologies and their convergence with other emerging technologies.

With those considerations in mind, Army's initial assessment of quantum technologies focuses on the following four key areas.

Quantum sensing and microscopy

The most immediate technologies and applications in positioning, navigation and timing, detection of gravitational and magnetic anomalies and microwave spectroscopy are highly valuable and are lowest in technological risk.

These will likely yield important capabilities of navigation in GPS-denied situations, enhanced detection of sub-surface structures and vehicles, awareness and locating of electromagnetic emitters and enhanced radar.

The application of human-machine interfacing through wearable magnetoencephalography[3] is highly valuable in how it could transform teaming with information and autonomous systems. It is also very high in technical risk and most distant in time.

The direct utility of the other applications and technologies in land operations is unclear and warrants further evaluation.

Quantum communications and cryptography

The value of Quantum Key Distribution (QKD) to Army is unproven because of the advent of post quantum cryptography methods that can be more easily integrated nor is it likely to be sufficiently secure on its own. The likelihood is that QKD enabled networks will be limited to a few high priority links (for example, at the operational and strategic levels) due to technical constraints, and their vulnerabilities.

The longer-term possibilities of networked quantum devices and memories, and clock synchronisation are highly valuable due to their ability to multiply the effects of other quantum and classical technologies, albeit also high in technological risk.

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3 Magnetoencephalography is a non-invasive technique for investigating human brain activity. It's a neuroimaging technique for mapping brain activity by recording magnetic fields produced by electrical currents occurring naturally in the brain, using very sensitive magnetometers.

Quantum computing and simulation

Quantum computers likely have many high value applications in Land operations. They can be divided between those that can be implemented in the near term using Noisy Intermediate Scale Quantum (NISQ) devices, and those that require the more distant error-corrected (EC) devices.

The nearest term and lowest technological risk being in delivering enhanced image/signal processing, planning and autonomous systems.

The more distant and higher technological risk applications being in modelling, intelligence gathering, cyberwarfare and cryptography. Having said that, all forms of quantum computing remain relatively high in technological risk.

Enablers and countermeasures

Post quantum cryptography is an important countermeasure of quantum computers capable of cryptography and should be a priority.

Other countermeasures are simpler technologies that may be used to ensure some technology parity with quantum-enabled opposing forces and should be developed alongside quantum technologies to mitigate risks and possible threats.

The enablers define the supply chains and infrastructure that are important to the sustainment of future quantum capabilities.

Vision

Based upon table 1, a vision for the most-likely evolution of quantum technologies for the land domain over the next 20 years is described in table 2.

Near term (5-10 years)	Intermediate term (10-15 years)	Far term (15-20 years)
• Quantum navigation systems employed in major vehicles and airframes. • Field-deployable quantum ground sensors used to image sub-surface anomalies. • Quantum-enhanced timing in digital communication networks. • Experimentation of QKD in operational and strategic level communication. • Post-quantum encryption introduced into communication systems. • Mainframe quantum computers enhancing planning in operational and strategic level headquarters. • Strategic and operational level countermeasures for quantum communication	• Quantum navigation systems employed in minor vehicles and airframes as well as autonomous vehicles. • Air and ground quantum sensors used to image sub-surface and concealed structures and vehicles. • Networks of quantum spectrometers used to detect and locate electromagnetic emitters. • Chip-scale analysers assisting medical and environmental monitoring. • Synchronisation of quantum networked clocks for improved communications and sensor correlation. • Regular use of QKD in operational and strategic level communication. • Widespread use of post-quantum encryption in communication networks. • Distributed and edge quantum computers enhancing signal/ image processing in Intelligence, Surveillance Reconnaissance (ISR), and machine learning in autonomous systems. • Spoofing countermeasures to quantum sensors being introduced for concealment and deception.	• Quantum spectrometers enhancing radar systems. • Quantum networks of sensors used for large-area monitoring and enhanced detection. • Experimentation with human-machine interfacing using quantum sensors. • Secure quantum communications with centralised mainframe quantum computers. • Edge and distributed quantum computers integrated throughout the information network. • Quantum computers assisting with modelling, intelligence gathering, cyberwarfare and cryptography. • Cyberwarfare tools for disabling quantum computers to be ready.

Table 2: A vision of the most likely evolution of quantum technologies for the land domain over the next 20 years.

Global Quantum Technology Environment

International landscape

Global quantum technology research and industry have grown swiftly since 2015 as nations and major corporations have significantly invested in technology development and national strategic policies have emerged. This rapidly evolving landscape can be characterised by:

- **National strategies, agendas, initiatives and programs.** Many of the world's leading nations and unions in quantum technology have declared national strategies, or initiatives.[4] In general, the policies are focussed on accelerating research and development, developing industry ecosystems, workforce education, industry transformation and community awareness, and investing in infrastructure (for example, national quantum computing centres, quantum communication networks, and fabrication facilities). Some countries, (for example the United Kingdom), place particular emphasis on sovereign capability and technology independence.
- **Investment and new ventures.** The national strategic policies have generally been accompanied by significant public funding by each of the United Kingdom, Germany, Russia, European Union, India and United States, and greater than US$14 billion by China. Since 2012, more than 52 quantum technology companies have been founded. These companies have received greater than a total of US$1 billion of venture capital investment. In addition to these figures, large technology companies such as IBM, Google, Microsoft, Amazon and Alibaba have made significant undisclosed investments as indicated by their substantial quantum computing programs.
- **Patent portfolios.** The portfolios of patents accumulated by different nations since 2012 indicate their different preferences and approaches to quantum technology investment and development. China's portfolio is dominated by patents of quantum communication technologies, whereas Canada's and the United States are dominated by patents of quantum computing technologies. Others, such as Japan and the United Kingdom balance across the different technology types.
- **Industry engagement.** Companies are either actively seeking to understand and assess quantum technologies and their implications or are seeking a first-mover advantage. Some have already invested in experimentation, application discovery and technology development; covering both Defence and non Defence applications.

4 This includes: United Kingdom, United States of America, European Union, Germany, India, Canada, Japan, Netherlands, Singapore, South Korea, Israel, China and Russia.

The rate and scale at which the international landscape is growing and evolving means that Army must act decisively if it wishes to gain advantage through quantum technology.

Domestic landscape

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) recently surveyed the domestic quantum technology landscape, assessed Australia's potential quantum industry and made key policy recommendations. CSIRO concluded that Australia has a rare strategic strength in quantum technology research. This world-class quantum technology research capability has been acquired over two decades of sustained and significant public funding. This has built over 22 quantum-related research institutions around Australia (primarily located within universities), including two quantum-focussed multi-institutional Centres of Excellence with over 400 researchers (Engineered Quantum Systems [EQuS] and the Centre for Quantum Computation and Communication Technology [CQC2T]).

Of these, eight universities are performing well above world standard in quantum physics research and together, the institutions are achieving 60% higher normalised citation impact than the global average. Furthermore, our quantum researchers are globally connected and have attracted partnerships with various international organisations, such as the United States of America Department of Defence and Government, Microsoft, IBM, Lockheed Martin and Google.

The CSIRO assessed that Australia has the potential to produce a quantum industry that generates over $4 billion in annual revenue per year and has created 16,000 new jobs by 2040. However, it is widely argued that these are underestimates of the potential value. This is principally because they do not include the value generated by quantum technologies in other industries (for example, improved productivity resulting from the use of quantum technology).

The domestic quantum industry has emerged rapidly since 2017. There are now over 16 quantum-related companies, which have together received over $125 million in funding and investment. Their activities span technology types, hardware, software and consultancy.

The CSIRO identified four key enablers for the continued growth of the domestic quantum industry:

1. **Focus.** Focus and coordinate Australia's quantum industry development efforts.
2. **Capability.** Build Australia's quantum workforce and infrastructure capabilities.
3. **Collaboration.** Support productive collaboration with local and international partners.
4. **Readiness.** Enhance the readiness of governments, society and end-users for next generation quantum technologies.

The critical requirements for these enablers may be identified as:

- national strategy, leadership and cooperation
- significant and sustained public and private investment
- early-adopters who focus technology development and demonstration
- policy that supports appropriate domestic and international collaboration, and
- education and awareness.

The implementation of which demands a Whole-of-Government (WoG) approach to building the domestic quantum industry. Owing to the substantial Defence interest in the domestic quantum industry, Army could have a substantial role to play in this WoG approach.

Current Defence Science and Technology Group activity

There are already quantum technology related efforts throughout Defence. Current activities in quantum technology led by the Defence Science and Technology (DST) Group are distributed across the key quantum technology streams of quantum sensing, quantum communications, quantum computing, and timing (atomic clocks).

The major activities include:

- Quantum Technology Theme of the Next Generation Technology Fund (NGTF) which has funded 11 three-year research projects with universities and small-to-medium enterprises, focussing on the development of fundamental quantum sensing, quantum communication, and timing technologies. The participating university research groups and small-to-medium enterprises constitute the NGTF Quantum Research Network.

- Quantum Assured Position, Navigation and Timing (PNT) Science, Technology and Research (STaR) Shot program which is addressing the ability of Australian Defence Force assets to operate in a contested environment where access to PNT information from Global Positioning System (and other similar satellite-based systems) may be degraded or denied. Quantum sensing PNT technologies and quantum-based atomic clocks are being developed specifically to address this need.
- International engagement, including the Australian/US multi-disciplinary University research initiative program in quantum computing and a PhD exchange program with the United Kingdom.
- NSW defence industry Quantum Research Consortium. A joint funding scheme with the NSW Defence Innovation Network that has funded two prototyping projects led by NSW universities with industry involvement.
- Supporting activities within the EQuS and CQC2T Centres of Excellence, and the Sydney Quantum Academy.

The initiatives outlined above provide Defence the landscape to examine opportunities to engage early with our whole of government, academic industry and international partners. Shaping and guiding these technologies as they develop facilitates the opportunity to transition technology concepts into capability for the warfighter.

It is within this landscape, and in support of broader Defence efforts, Army will be seeking to achieve, sustain and maximise a quantum advantage. This is based upon the premise that the most highly disruptive and advantageous applications of quantum technologies for the land domain may not yet be identified.

The Army Roadmap for Quantum Technology

Army strategic guidance

The *2020 Defence Strategic Update, 2020 Force Structure Plan*, and the DST *More, Together: Defence Science and Technology Strategy 2030,* highlight the disruptive nature of quantum technologies. Army strategic guidance for this Roadmap is derived from *Accelerated Warfare: Futures Statement for an Army in Motion* and *Army in Motion: Army's Contribution to Defence Strategy, second edition* further highlight the impact of emerging technology.

Two major technology drivers of *Accelerated Warfare* that will be impacted by quantum technologies are:

- **Robotic and autonomous systems.** The convergence of big data, artificial intelligence, machine-learning, robotics, unmanned and autonomous capability with precision weaponry. Army issued its *Robotic and Autonomous Systems Strategy* in 2018.
- **Cyber and information warfare.** The capture, fusion, synthesis, assurance and security of information for decision superiority.

Key themes of *Army in Motion* that define Army's approach to quantum technologies are:

- **Adaptive thinking.** Army will increase the speed at which it adapts to change by using the model 'think big, start small, and move fast'.

  Army's people must respond to Accelerated Warfare by pushing themselves to think in creative and unconstrained ways, to challenge existing concepts and tactics, and to pair new capabilities with imaginative and novel thinking.

- **Partnering.** Army's success depends on strong partnerships within Defence and with WoG, industry, academia, the Australian community, and our allied and military partners. Partnerships with industry and academia enable Army to explore and quickly adopt emerging and disruptive technologies and create opportunities for enhancing army-to-army engagement.
- **Sovereign industry.** A sovereign industry base is a source of strength for Army. Army will work to ensure supply integrity and capacity for rapid technological development. Army will support Australian industry to pursue defence export opportunities.
- **Integration.** Army generates teams for the Joint and Integrated Force,

and so must have complementary and compatible systems. For example, Army will develop an information warfare capability and increase its contribution to national cyber security.

Aim and implementation

Army's aim is to gain and retain an early quantum advantage for the land domain by:

- **Establish.** Rapidly establishing a quantum innovation ecosystem focussed on the land domain.
- **Identify.** Identifying the most disruptive and advantageous applications of quantum technologies for the land domain before competitors.
- **Develop.** Developing the related technology, operating concepts and modified force designs before competitors.
- **Support.** Supporting the Defence quantum technology strategy as it develops.

Army's approach to these objectives is to pursue four Lines of Effort (LoE):

- **Collaborate.** Create an Army Chapter of a Defence Quantum Innovation Community.
- **Explore.** A rapid quantum application discovery and testing cycle.
- **Exploit.** Technology, operating concept and force design development.
- **Refine.** Curation of quantum technology understanding, landscaping, assessment and strategy.

These LoE form the system depicted in figure 1. The key activities and milestones of each line of effort are described in the following subsections. The activities and milestones of each line of effort are organised into three distinct phases that are sequenced across the lines of effort as depicted in figure 2.

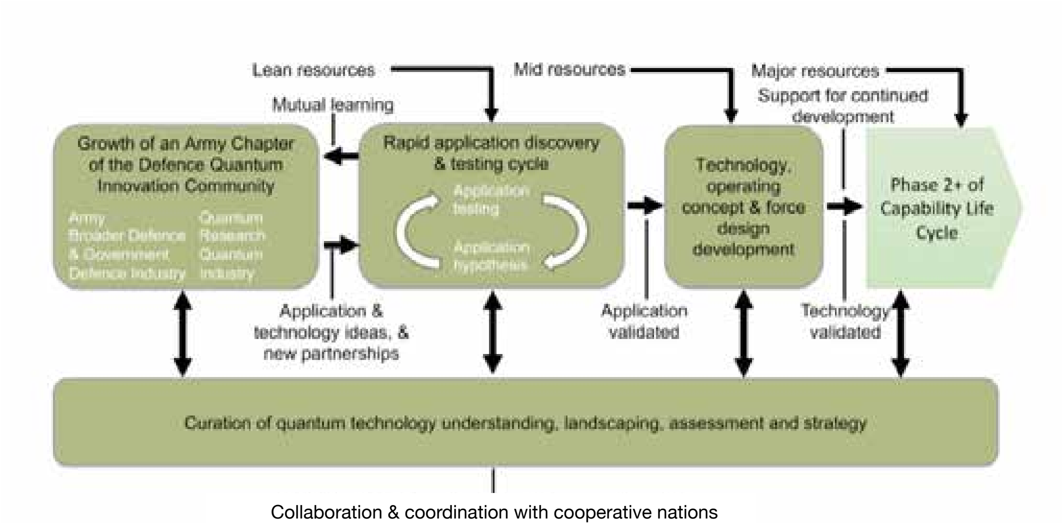

Figure 1: Army lines of effort and their formation of a continuous process that yields a quantum advantage for the land domain.

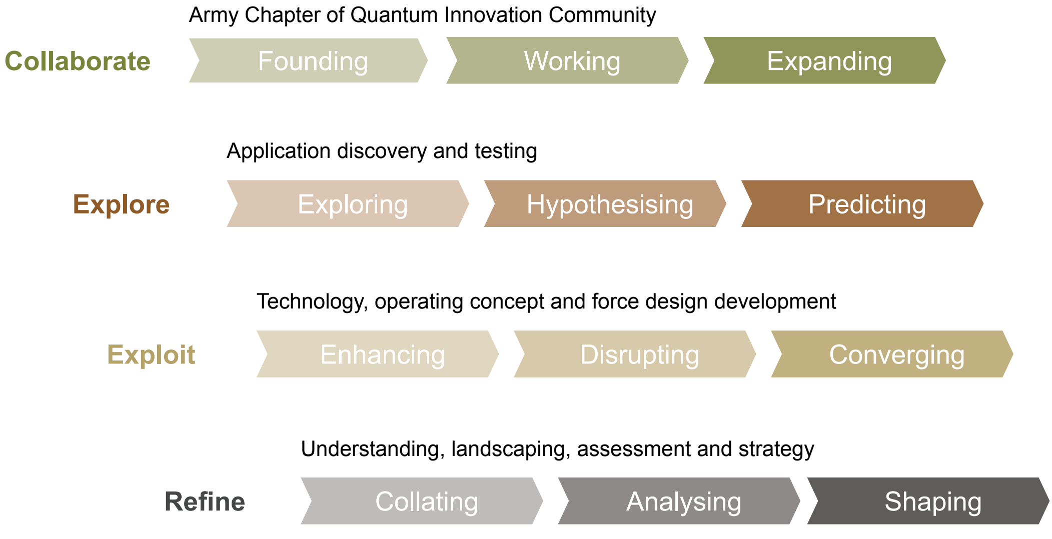

Figure 2: Army lines of effort for the exploitation of quantum technology.

LoE1: Collaborate

Growth of an Army Chapter of a Defence Quantum Innovation Community.

The vision for the Army Chapter is a collaborative community drawn from quantum research, quantum industry, Army and broader Defence and defence industry that is focussed on the application of quantum technology for the land domain. Its primary function is to generate new concepts and technology ideas that can then be exercised and tested. This will lead to mutual learning, which is then fed back to refine and catalyse the next generation of ideas and partnerships.

Its secondary function is to support the broader aims of the Defence Quantum Innovation Community, including quantum education and awareness in Army, broader Defence and defence industry.

These functions can be actioned through regular workshops, networking and awareness events, newsletters and discussion papers, and the compilation of reports and education/awareness materials.

The Army Chapter will develop through three phases:

- **Founding.** Initially founded by members of quantum research, quantum industry, defence primes and quantum-engaged defence Subject Matter Experts (SMEs), DSTG, Future Land Warfare Branch (chaired by Robotic and Autonomous Systems Implementation Coordination Office [RICO]), and the established Next Generation Technologies Fund (NGTF) Quantum Research Network and NSW defence industry Quantum Research Consortium. Key tasks in this stage are to establish an initial mutual understanding of the quantum landscape, motivations and interests of members, Army's approach to quantum technology and understanding of initial opportunities for quantum technologies for the land domain.

- **Working.** Focus on working together to build the portfolio of concepts of technologies and awareness materials to support the next stage.

- **Expanding.** Expand Chapter membership to broader Defence and defence industry through awareness and demonstration activities. This expansion will bring diversity and acceleration of understanding, applications and technologies.

LoE2: Explore

A rapid quantum application discovery and testing cycle.

This is implemented through regular Army Quantum Technology Challenges. Their primary functions are to test hypotheses about applications, collect ideas for applications, and via successive iterations, rapidly sort and converge to disruptive land domain applications through mutual learning. These Challenges will be cognisant of broader Defence efforts in quantum technology.

This learning will likely proceed through three distinct phases:

- **Exploring.** Experimenting with a broad range of technologies and applications to gain experience and understanding.
- **Hypothesising.** Through exploration experience and hypothesis testing, develop heuristics about the types of applications where quantum technologies can deliver the greatest and most transformative advantages for Army.
- **Predicting**. Applying the developed heuristics to predict high value applications and forecast their convergence with other emerging technologies.

The choice of Challenges will be informed by the priorities in table 3. A portfolio approach has been applied in the selection of these priorities to balance technical risk and potential application value over all technology types. Thereby recognising the diversity of quantum technologies and that their most disruptive applications are likely undiscovered.

Technology type	Priority 1	Priority 2	Priority 3
Sensing and imaging	• Positioning, navigation & timing • Gravity and magnetic anomaly detection	• Electromagnetic detection & ranging • Medical & environmental sensing	• Human-machine interfacing • Material and device characterisation
Communications and cryptography	• Point-to-point QKD • Network clock synchronisation	• Multi-point QKD • Long-lived encrypted quantum memories	• Networking quantum sensors and computers • Integrated quantum-classical networks
Computing and simulation	• Image/signal processing • Optimisation of logistics and planning	• AI/ML and robotics • Cyberwarfare tools • Cryptography • Operational simulation	• Geo/physical modelling • Materials, biotechnology and nanotechnology simulation
Enables and countermeasures	• Post-quantum cryptography • Disrupting QKD	• Characterisation benchmarking and optimisation tools • Spoofing quantum sensors	• Scalable manufacturing • Disabling quantum computers

Table 3: Initial prioritisation of land domain applications of quantum technologies.

Army has deliberately chosen not to be technology led, which would lead to prioritising technical readiness over application value. Importantly, the priorities and the design of Challenges, will change as Army learns through successive cycles and its needs and understanding evolve.

The objective of each Challenge is to test if quantum technologies can deliver advantages in a specific application. To achieve this, participating teams will need to:

- demonstrate the application in a simulated environment and workflow using simulations and/or an early proof-of-concept prototype of a specific quantum technology (that is, Technical Readiness Level [TRL] 3-4)
- present an initial estimate (as supported by the demonstration and critical analysis) of the advantages (if any) that can be attained, the requirements for delivering those advantages and the development roadmap to meet those requirements.

Those applications, technologies and teams that promise significant advantages and have a credible development roadmap will be advanced. All Challenge outcomes, application ideas, technology information, and capabilities of teams will be collated into a database that will inform the fourth line of effort.

The establishment of simulation and testing sandpits is key to the execution of the Challenges and to support the technology and operating concept development. These secure sandpit facilities need to provide the computational resources required for simulation as well as software or apparatus that emulate Army use case workflows, data and environments with escalating levels of complexity and fidelity. As the Challenges evolve in time and new applications are discovered, the requirements of this sandpit will also evolve. This will place demands on the managers and developers of the sandpits as well as on Army to readily collate data about different workflows and environments.

LoE3: Exploit

Technology, operating concept and force design development.

In this line of effort, activities will develop prototypes of the technologies identified by the Challenges to the level where they can demonstrate new operating concepts in relevant/realistic environments and workflows so that Army can understand their value proposition.

Following the successful demonstration of a valuable operating concept, a preliminary analysis of the integration of the technology and operating concept into existing Army and broader Defence technologies and operating concepts will be performed. This analysis will inform future force design and statement of needs that clearly defines the opportunity and requirements for the technology to progress towards acquisition, if appropriate.

The purpose of the statement of needs is to focus the technical development required for progression and to provide the evidence to build industry partnerships and/or to raise the necessary capital to implement the technical development. Army will seek to support teams to execute this development by facilitating connections in the Chapter and broader industry and introductions to entrepreneurial programs.

As Army's experience and understanding of quantum technology evolves and new applications of quantum technologies are discovered, the focus of technology, operating concept and force design development will likely evolve through the following three phases:

- **Enhancing.** Here, the focus is on how quantum technologies can offer an advantage by replacing existing technologies in existing operating concepts or enabling incremental modifications of operating concepts.

- **Disrupting.** The focus is now on identifying how singular technologies or applications can transform Army's capabilities and how it operates.
- **Converging.** Finally, the focus turns to how quantum technologies combine with each other and other emerging technologies to transform Army's capabilities and how it operates.

LoE4: Refine

Curation of quantum technology understanding, landscaping, assessment and strategy.

This line of effort has three outcomes:

- collate and analyse knowledge and capabilities generated by the other lines of effort and maintain global situational awareness in quantum technology through continuous landscaping, scanning and assessment via the network
- refine Army's quantum technology roadmap, and provide advice and inputs into defence and national strategy, and Defence Export Controls, and
- coordinate quantum technology activities with other Services and Groups, broader government and cooperative nations.

This line of effort is expected to broadly evolve through three phases:

- **Collating.** Initially, the focus will be on collating the information generated by the other lines of effort while continuing to survey quantum technologies, their applications, and the domestic and international landscape.
- **Analysing.** The focus will shift to assessing quantum technologies, their development risk and timelines, the value and disruptive potential of their applications, and domestic and international capabilities, while also analysing global supply chains, production capabilities, and defence and industry progress.
- **Shaping.** Finally, the focus is on precision shaping of quantum technology capability generation for Army, and supporting WoG approaches to industry growth, supply chain and production security, Intellectual Property protection and Defence export controls.

Conclusion

Quantum technologies potentially offer profound advantages in land warfare. As a consequence, Army is in an intensifying global competition to understand, co-develop and exploit quantum technologies for the land domain. This is a competition where Army can achieve a significant advantage by harnessing the outcomes of quantum technology research through wider Defence led activities as well as whole of government, academic, industry and international partners.

This Roadmap is Army's critical first move for the development and application of quantum technologies for the land domain.

This Roadmap communicates Army's current vision and assessment of quantum technologies, and their application to the land domain. Army's intention is to engage with Australia's quantum technology community, broader defence, industry and government.

Annex A: What is Quantum Technology?

This technical annex expands upon the brief introduction to quantum technology provided in the main text. It provides additional details of the definition and characteristics of quantum technologies as well as further discussion of their key operating principles, capabilities, limitations and defence applications.

Definition

A quantum system is a system of elementary particles or quasi-particles (for example, electrons, photons and nuclei) whose behaviour is governed by the laws of quantum physics (see figure 1). Measurements of a quantum system have random values whose probabilities are determined by the system's overall state at the time of measurement. Following measurement, a quantum system is projected into a state that matches the measurement mechanism and value.

A quantum system's state at a given moment can be described as a superposition of the states associated with a measurement mechanism: in effect the simultaneous occupation of multiple states with definite relative amplitudes and phases. Some states exhibit entanglement of two or more sub-systems (that is, sub-groups of particles) of the quantum system. Entanglement produces statistical correlations in the values of measurements of the individual sub-systems. Interactions between a quantum system and its environment can randomise its state. This process is called decoherence and it ultimately limits how precisely a quantum system's state can be engineered.

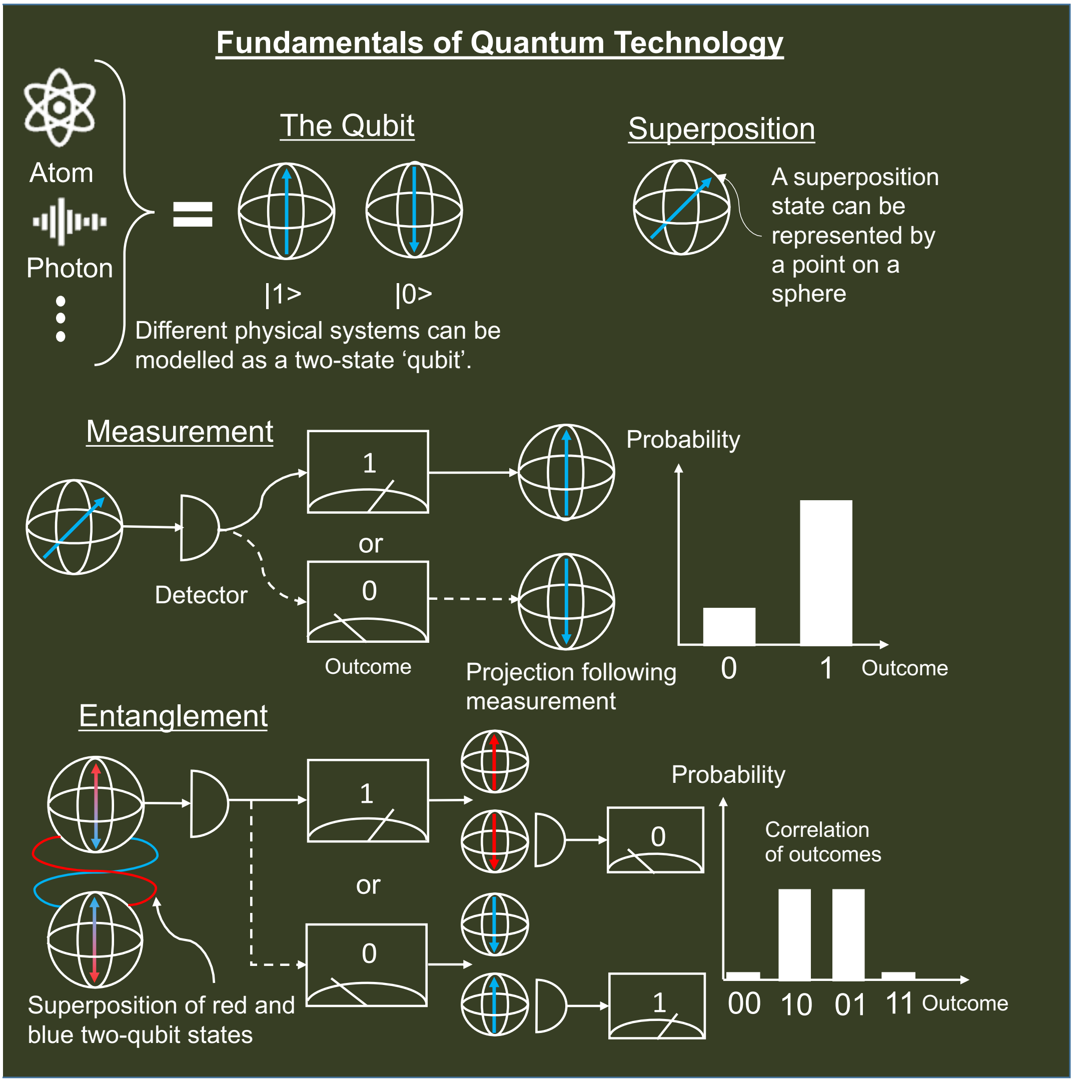

Figure 3: Fundamental concepts of quantum technology.

Characteristics

The performance of a quantum technology is determined by both its qubits and its classical control system and method. Performance is improved by engineering higher quality qubit systems, classical control hardware and methods, and shielding the qubits from the environment.

The first three are pushing the limits of material growth, microfabrication, electrical, optical and mechanical engineering, and optimal control design. Environmental shielding requirements depend on the type of technology and qubit system. Some require cryogenics to achieve ultra-low temperatures and/or vacuum systems to achieve ultra-high mechanical isolation. Others do not require either and can operate in ambient and extreme conditions. Nevertheless, high quality materials, fabrication and device engineering is key to high performance quantum technology.

Quantum sensing and imaging

Quantum sensors measure time, dynamics (that is, forces, acceleration and rotation), and fields (that is, gravitational, electromagnetic and mechanical) with unprecedented precision and stability. Imaging is an extension of quantum sensing where quantum sensors are combined with an imaging apparatus (for example, a probe that scans the position of the sensor, an array of sensors or a beam of electromagnetic waves prepared in a quantum state) to perform high-resolution microscopy or macroscopy (for example, radar) with unprecedented sensitivity.

Quantum sensors exploit quantum superposition to apply interferometry techniques to detect small changes in a qubit's state through the passage of time, dynamics or interactions with fields. Quantum entanglement between multiple qubits may be exploited to further enhance precision. Stability is achieved through the qubits having fixed and universal susceptibilities (for example, electron gyromagnetic ratio and atomic mass).

The limitations of quantum sensors are primarily their dynamic range, speed and environmental exposure. Although highly sensitive, quantum sensors are often limited to a small range of measurand values and will saturate if there are large variations. Quantum sensors may take longer to perform measurements than other technologies, and so cannot provide the same update rate. The environment can bring unwanted noise that deteriorates the qubit properties and so the qubits have to be shielded from the environment elements. This is the classic packaging problem experienced by all sensors.

The first two limitations can be ameliorated by integrating quantum sensors with other sensors that are faster and have larger dynamic ranges. The third limitation is a difficult problem, but one where there is an established wealth of knowledge to draw upon, and thus reason to be optimistic.

The most promising defence Quantum technology applications are:

- **Enhanced positioning, navigation and timing.** Quantum accelerometers, magnetometers, gyroscopes and clocks promise the long-term stability and precision required for accurate inertial navigation in the absence of GPS. Furthermore, advanced atomic clocks promise the precision timing that is key to accurate positioning as well as reducing the errors and increasing the speed of digital communications. All of which, can be used to enhance the performance of robotic and autonomous systems, missile systems, C4I systems and fire control systems.
- **Enhanced situational awareness.** Quantum gravimeters and magnetometers promise new capabilities in geospatial mapping and anomaly detection, for example, the detection of subterranean structures or objects which could impede autonomous systems. Quantum microwave spectrometers promise high sensitivity and unbroken detection bands for monitoring the electromagnetic spectrum. These could enhance the range and precision of existing radar systems or, if networked, enhance the detection and locating of electromagnetic emitters.
- **Enhanced medical and environmental analysis.** Quantum nanosensors offer unprecedented means to perform biological and chemical sensing and imaging for medical diagnosis and treatment and environmental testing and monitoring. The technologies range from sensitive nanoparticles that are injected into a specimen and tracked/imaged, to field-deployable lab-on-a-chip biochemical analysers to add-ons that enhance the resolution of existing medical imaging techniques, such as Magnetic Resonance Imaging (MRI).
- **Enhanced human-machine interfacing.** Quantum magnetometers may enable wearable high-resolution magnetoencephalography for real-time brain activity imaging - a key ingredient to practical non-invasive cognitive communication with machines.

- **Enhanced defence science and industry.** Quantum microscopes, spectrometers and nanosensors promise to drive innovation in materials science and nano-, bio- and medical technology. For example, quantum microscopes are a critical characterisation tool for the development of low energy two-dimensional (for example, graphene) electronics and could potentially accelerate drug design by providing a more direct and functional means to image the chemical structure of proteins and other complex molecules which are key to microbiological processes. Additionally, chip-scale Nuclear Magnetic Resonance (NMR) spectrometers promise the democratisation of precision chemical analysis, whose restricted availability is a profound constraint in current biological, chemical and material research and development.

Quantum communications and cryptography

Quantum communications can be used to network quantum sensors to correlate and enhance sensitivity over large areas (for example, synchronise clocks within a communication network) and networking quantum computers to efficiently exchange data and amass computational power.

Quantum communications may also be used to securely access remote quantum computers or securely transmit data between classical devices (for example, distribute encryption keys). This is known as Quantum Key Distribution (QKD) and is a means to enhance the security of communications by enabling the secure distribution of one-time private encryption keys between remote nodes of a conventional encrypted network.

Predominately, quantum communication is achieved by sending superimposed or entangled qubits between devices. The qubits are fundamental particles of light (that is, photons) and thus quantum communications can be seen as the ultimate limit of optical communications. Like current optical communications, quantum communication can be performed between remote nodes using optical fibre links, direct free-space (that is, line-of-sight) links or satellite mediated links between ground stations. Quantum repeaters are required to overcome losses in fibre networks, to synchronise communications in complicated networks and to enable over-the-horizon communication via satellite links. Quantum repeaters must be able to collect, store and regenerate qubits with high probability and fidelity. Networking quantum sensors and computers requires an additional technology: quantum ports that interface the photons acting as the communication qubits with the physical qubits of the sensor/computer.

Alternatively, quantum communication can be achieved by the transportation and exchange of long-term quantum memories between parties likened to exchanging encrypted hard drives or documents.

Security is physically assured in quantum communications by the projective nature of quantum measurements, which means it is not physically possible to copy the qubit encoded information without modifying it. Thus, security is assured in the sense that interception and interference can be detected with a known statistical confidence. The confidence level depends on the number of transmitted qubits sacrificed to distil the encryption key and thus amplify privacy and the noise present in the communication channel.

There have been demonstrations of QKD over optical fibre networks, direct free-space links and satellite mediated links. However, these have not included quantum repeaters and so have been limited in range (without the use of ‘trusted’ intermediary nodes) and limited in the complexity of their network traffic without the ability to use repeaters to combine scheduling with routing. The creation of quantum repeaters, ports and long-lived memories is technically challenging and there is still some way to go before these will be sufficiently mature to enable quantum communication networks.

The rate of quantum communication (that is, key generation rate) is currently relatively slow and presents significant technical challenge to improve. Thus, widespread QKD or quantum networking is unlikely in the near future. Rather quantum communications are likely to be restricted to a few high priority links.

Defence applications of quantum communications include:

- **Enhanced security of communication via QKD.** QKD offers a means to securely distribute one-time private encryption keys and so enhance the security of the encrypted communication over public key encryption methods.

  Public key encryption relies on the difficulty of solving certain mathematical problems (for example, semi-prime factoring) rather than a physical effect (such as that underpinning QKD) to maintain security. Thus, if an efficient way of solving these mathematical problems is developed (for example, a quantum computer), the effectiveness of public key encryption is dramatically reduced. Private key encryption does not suffer this weakness, however, private keys should only be used once, which means that keys must be securely distributing at a sufficiently high rate to service the traffic of a network.

  A QKD network operating in parallel with the conventional communication network addresses this problem.

- **Enhanced network synchronisation.** Distributing entanglement can be used as a physical means of precisely synchronising distant clocks to improve the speed and accuracy of digital communications as well as the correlation of distant classical sensors to more precisely detect and/or locate anomalies.
- **Enhanced sensitivity and large-area quantum sensing.** Quantum communications may be used to entangle quantum sensors. Entangling multiple quantum sensors at a single location improves their combined sensitivity beyond that offered classically. Entangling distant quantum sensors enhances their ability to simultaneously correlate their measurements and so more precisely detect and/or locate anomalies.
- **Enhanced security and performance of quantum computing.** Quantum communications can enhance the efficiency of data exchange between quantum computers, amass their computational power and enable secure access to them. Networking quantum computers is expected to enable a similar expansion in performance and applications as the internet has enabled for classical computers.

Quantum computing and simulation

Quantum computers dramatically speed-up the solution of certain computational problems. While the full range of such problems is still being discovered, established examples are related to signal/image processing, machine learning, optimisation, simulation, searching and factoring. They achieve this by exploiting quantum superposition and entanglement to represent and manipulate information in a fundamentally more dense and efficient way than classical computers. Thus, quantum computers require fewer physical resources and operations to solve the same problem as a classical computer.

It is important to note that quantum computers have a slower ‘clock rate’ than classical computers, thus they will not speed up calculations that are already fast on classical computers. Rather, a way to look at it is that they will take seconds to perform a calculation that would take days or years or even longer on a current computer, thereby making certain calculations practical for the first time.

The advantages of quantum computing is that, for a given calculation time, quantum computers deliver a more accurate or comprehensive solution than a classical computer, which is relevant to situations were accuracy is more important than speed.

The key performance metrics of quantum computers are:

- number of qubits – the amount of information that can be encoded and processed by the computer
- program/circuit depth – the complexity of the algorithms that can be performed by the computer
- speed – the time it takes to perform a computation
- fidelity – the precision of the computation (how unlikely errors are).

Quantum computers are currently in what is known as the Noisy Intermediate-Scale Quantum (NISQ) era, where they have relatively few qubits, achieve short circuit depths and have low fidelity. In this era, random physical errors in the hardware operations accumulate during a computation and thus limit their performance and the types of computations they can perform. Consequently, to realise an advantage over classical computers, the programming of NISQ era computers must be optimised for the computer's specific hardware architecture (like the early days of classical computers). Different hardware architectures have different strengths and weaknesses, and they are suited to different applications. Hence, the benchmarking of hardware architectures and pursuit of optimal programming is critical in the NISQ era.

The types of applications where NISQ computers will likely deliver advantage over classical computers are applications that can tolerate error, have sufficiently few inputs and outputs to be encoded by the limited number of qubits, yet involve sufficiently complex problems for the efficiency gains of quantum computation to be beneficial. These applications are most likely found in signal/image processing, simulation, machine learning and optimisation.

The next era for quantum computers is the error-corrected (EC) era, where the number of qubits, circuit depths and fidelities have crossed thresholds that enable the implementation of methods that correct the random errors. In this era, logical-level programming no longer needs to be hardware specific and quantum computers achieve their widest utility, including applications in optimisation, searching and factoring. Reaching the EC era is a significant technical challenge and is considered at least five years away for some hardware technologies and longer for others.

The future of quantum computing is one of diverse hardware that is integrated with classical computers throughout an information network. Different hardware technologies are suited to different roles in the network: centralised mainframe or massively-parallelised cluster, distributed and edge. Those technologies that require cryogenic cooling or fragile control systems are better suited to mainframe computing roles in centralised cloud/supercomputing facilities. Those that are more readily networked via quantum communications are better suited to forming distributed quantum computing networks. As well as those that have low size, weight and power and can be deeply integrated with classical computers are better suited to massive-parallelisation in centralised cloud/supercomputing clusters, integrated into distributed classical computers and deployed in mobile/edge computing devices. In all roles, quantum computers will be integrated with classical computers to some degree and act as an accelerator of specific computing tasks, akin to graphics accelerators of today. Thus, quantum computers should be not viewed as replacements of classical computers, but augmentations and a continuation of the current trend towards computing hardware specialisation and diversification.

A key conclusion of this future vision of quantum computing is that a portfolio of complementary hardware technologies is required to fully exploit quantum computing across a defence information network in both the NISQ and EC eras. Integration of hardware and software with classical computers is a critical pursuit.

Quantum computing has many potential defence applications, including:

- **Enhanced signal and image processing and searching intelligence, surveillance and reconnaissance.** Edge quantum computers potentially offer a leap in the ability to filter, decode, correlate or identify features in signals and images captured by edge ISR devices. This reduces network congestion associated with streaming the raw data to centralised computers for processing. Distributed and centralised quantum computers may dramatically expand the capacity to search and extract intelligence from large unstructured databases.
- **Enhanced optimisation of plans and logistics.** Quantum computers may be employed at various levels to provide timely optimisation of complex plans and logistics systems.
- **Enhanced artificial intelligence/machine learning in automation, robotics and cyberwarfare.** Quantum computers promise to accelerate machine learning sub-routines, learning and model optimisation, enabling enhanced performance and possibilities like in-mission relearning. The combination of enhanced signal/imaging processing, optimisation and machine learning may also improve decision making in autonomous systems and robot populations, as well as new cyber tools.

- **Enhanced operational simulation and geophysical modelling.** Quantum computers can accelerate the identification simulation of stochastic dynamics, such as those that occur in operations, and systems described by complex differential equations, such as fluid dynamics in weather, ballistics and ocean dynamics. This improved simulation will support superior decision making.
- **Enhanced defence science and industry.** Quantum computers offer unprecedented capabilities in the simulation of complex molecules and materials, which will accelerate innovation in bio-/nano-technology and materials engineering. Quantum computers can also support enhanced engineering design and process optimisation, leading to higher performing technologies and more efficient manufacturing.
- **New cryptography capabilities.** Quantum computers have the ability to break public key encryption protocols using efficient algorithms for factoring large numbers. This requires many error corrected qubits to achieve and is unlikely to occur within the next 10 years. This timeframe is within the lifetime of some cryptographic systems and so the potential threat of quantum computers needs to be considered when designing/specifying those systems. Other quantum decryption algorithms may be discovered in the near future, and as a consequence, quantum computers have stimulated a new development race between decryption methods and encryption protocols.

Quantum technology enabling technology

The performance of a quantum technology is determined by both its qubits and its classical control system and methods. Thus, the production and employment of high-performance quantum technologies are enabled by:

- **Quantum foundries.** Quantum foundries synthesise quantum systems from source materials. For example, the synthesis of high-purity semiconducting and superconducting materials and atomic/nano-scale engineering of qubits as defects within or through heterostructures of the materials. Foundries require significant infrastructure, plant and knowledge to produce high-performance quantum systems.
- **High-performance electronic, optical, mechanical and thermal systems.** These form the control systems and isolation systems of quantum technologies. For example, high-frequency and precision microwave components and microcontrollers (that is, similar to radar), high-resolution lasers and precise optical elements, ultra-high vacuum systems and cryostats. Global supply of such specialised and high-performance components is restricted.

- **Nano/micro-fabrication facilities.** Such facilities are generally required to manufacture devices that integrate the control systems with the quantum systems, such as nano-optical, -electronic and -mechanical structures. Similar to foundries, they require significant infrastructure, plant and skill.
- **High-performance software stacks.** Stacks of multiple layers of software are required to operate and apply quantum hardware with greatest effect. At the lower levels, this includes embedded programming of control systems, control optimisation and characterisation tools and compilers. At higher levels, this includes user interfaces, applications and interfaces with larger computing, communication and sensing systems. Development is currently occurring across all layers of the stack, with industry standards and architectures emerging, but not yet established.
- **Benchmarking, testing and simulation facilities.** Quantum technologies are generally entering a phase in their development where independent and trusted benchmarking and testing facilities are required to accelerate development and support user adoption. For example, various public supercomputing facilities have commenced programs to benchmark different quantum computing technologies. Such supercomputing facilities are also providing computing resources for the simulation of quantum technologies. Simulation is important to the identification, development and demonstration of applications in advance of the corresponding hardware maturing.
- **Quantum-ready workforce.** The design, production and employment of quantum technologies require scientists and engineers of multiple disciplines. Some are necessarily quantum scientists and engineers, but many others must be experts who have converted from other fields (for example, electronics, optics, software etc) to bring their specialist skills and experience that are otherwise absent in the new industry.

These enablers define the critical supplies and infrastructure of a quantum industry, and are thus important to the creation and sustainment of Army's future quantum capabilities.

Quantum technology countermeasures

There are a variety of possible countermeasures to quantum technology. Some are highly developed (for example, attacks on QKD protocols), some are emerging (for example, post quantum cryptography) and others are yet to be explored.

- **Post quantum cryptography.** The principal motivation for QKD is the potential threat posed by quantum computers to current RSA public key encryption protocols by their ability to efficiently factor the large numbers used in the protocols. It is unlikely that the EC quantum computers with sufficient qubits to perform this task will be developed within the next 10 years. An alternate way of countering this threat is to switch RSA encryption protocols to new post-quantum encryption protocols that cannot be efficiently attacked by quantum computers. There are a variety of such protocols and others likely under development. As they generally require changes to the hardware and software of existing communication systems their adoption needs to begin soon so that networks are 'quantum-resistant' before the advent of large EC quantum computers. Notably, post quantum cryptography largely reduces the need for QKD. The remaining requirement being that there is always the risk that new algorithms are discovered for either quantum or classical computers that can efficiently attack the post quantum encryption protocols.

- **Disrupting quantum communications.** Methods for attacking the security of QKD protocols have been developed alongside the protocols themselves. These vary from injecting optical noise into the communication link to rerouting the link and impersonating the receiver. Alternatively, since sensitive photodetectors are required to detect the transmitted photons, QKD systems can potentially be simply disabled temporarily or permanently using high power light pulses that overload or damage the photodetectors.

- **Spoofing quantum sensors.** Quantum sensors are susceptible to interference from the environment and so can potentially be spoofed by carefully engineered emissions from structures or vehicles that need to be hidden. For example, the universal fundamental properties that quantum sensors use to achieve long-term stability, mean they can also be efficiently targeted by tuned spoofing signals that alter or disrupt the measurements of the sensors. It does not appear that such spoofing technology is being publicly developed but is feasible.

- **Disabling quantum computers.** Quantum computers are complex, precisely calibrated and, in some cases, fragile machines. With adequate knowledge of their design, they can potentially be disrupted or disabled in various ways.

Greater attention needs to be applied to the development of countermeasures alongside quantum technologies and their applications. This will enable Army to capitalise on opportunities in quantum technology addressing the weaknesses that may emerge as a result.

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