Quantum Technologies

A new frontier for Systems Engineering?

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Contents

Introduction

The principles of quantum physics were discovered during the 'first quantum revolution', which occurred about a century ago thanks to the discoveries of Planck, Einstein, Bohr, Heisenberg, Schrödinger and many more.

Since its discovery, quantum physics has helped us understand the universe better than ever before and has resulted in many new devices that depend on that understanding, including the transistor and the laser.

Recently, due to our ever-increasing capability to precisely control individual particles and their physical interactions, we have become able to build new technologies that directly exploit the fundamental principles of quantum physics [1]. Our ability to do this is often referred to as the 'second quantum revolution' and is enabling the development of devices referred to as 'quantum technologies'. The applications of quantum technologies are vast, including quantum computing, quantum sensing and timing, and quantum communications and have a number of advantages over their classical (i.e. non-quantum) counterparts.

These advantages can deliver benefits in areas as diverse as environmental monitoring, health care and navigation. The quantum technologies being developed for these applications differ from previous technologies due to their reliance on uniquely quantum effects such as non-determinism and entanglement; these effects may allow such technologies to achieve significant advantages over their classical counterparts in certain applications. The 2023 McKinsey Quantum Technology Monitor indicates a vibrant and flourishing quantum ecosystem. It expects the global quantum computing market to reach $93 billion by 2040, with the overall quantum technology market potential estimated at $106 billion; quantum sensing, timing, imaging, and communications, each have an estimated market size ranging from $1 billion to $7 billion by 2040 [2]. The UK's Quantum Strategy is currently working to realise the advantages quantum technologies offer [3].

However, before the advantages of quantum technologies can be realised in practice, quantum technologies must be integrated into wider systems which incorporate both quantum and classical elements [4].

The standard approach to engineering applied to modern-day systems, which have become increasingly sophisticated and complex, is referred to as systems engineering. Systems engineering is an interdisciplinary engineering field, which focuses on how to design, integrate, and manage complex systems over their life cycles. This white paper will look at the application of systems engineering to quantum technology, in order to:

1. Highlight some of the challenges that quantum effects will pose to current systems engineering approaches and to explain the potential problems and risks that this may lead to;
2. Propose some initial strategies and actions which can be adopted in order to address these challenges and risks. These approaches are intended to minimise the disruption of this new technology to established systems engineering methodologies, whilst recognising the challenges that are presented to existing systems engineering approaches.

This paper first discusses the development of quantum technologies, before introducing systems engineering. This is followed by how SE for classical systems is challenged by introducing quantum technologies. Subsequent sections expand on these challenges before the paper concludes with recommendations.

References:
[1] It takes two to entangle – **a Dstl biscuit book**
[2] RHC_regulation_of_quantum_technology_ applications.pdf (**publishing.service.gov.uk**)
[3] National Quantum Strategy (**publishing.service.gov.uk**)
[4] Henshaw, Michael J. de C., et al. "The challenges for Systems Engineers of non-classical Quantum Technologies." arXiv preprint arXiv:1710.05643 (2017).

Challenges in the development of quantum technologies

Quantum technologies over the past 10 years have begun to move out of university laboratories worldwide and be tested in real world applications [5] [6] [7] [8]. To enable this, many technological and scientific challenges have had to be overcome.

Quantum technologies, due to the way they harness principles of quantum physics, are fundamentally different from classical technologies.

These differences, along with the current low state of readiness for quantum technologies, mean that there is much work to do to integrate them effectively into the multitude of desired applications and create exportable products that will result in economic benefits to the UK.

The key to addressing this challenge and enabling a rapid route to market is to ensure that the existing systems engineering methodologies used for classical technologies can be extended, or new methodologies created, to handle the unique properties found in the quantum case.

References:

[5] Bongs, Kai, et al. "Taking atom interferometric quantum sensors from the laboratory to real-world applications." Nature Reviews Physics 1.12 (2019): 731-739.
[6] Roslund, Jonathan D., et al. "Optical clocks at sea." Nature 628.8009 (2024): 736-740.
[7] Vovrosh, Jamie, et al. "Advances in Portable Atom Interferometry-Based Gravity Sensing." Sensors 23.17 (2023): 7651.
[8] Boto, E., Holmes, N., Leggett, J. et al. Moving magnetoencephalography towards real-world applications with a wearable system. Nature 555, 657–661 (2018). **https://doi.org/10.1038/nature26147**

Quantum navigation - application example

Many existing navigation systems rely on the use of global navigation satellite systems (GNSS), which use signals from satellites. However, while GNSS navigation can be very accurate, it is not always accessible. Obstacles, such as buildings and natural features, such as canyons, can block the satellite signals.

In addition to this, GNSS systems are also susceptible to jamming, imitation, or denial, resulting in negative impacts to platforms utilising GNSS in their navigation systems. It has been estimated that a single day of GNSS service denial would result in a cost of £1 billion to the UK [9].

When GNSS systems can't be used, a number of satellite-free navigation methods can be used, however such systems are limited in their effectiveness. For example, when using inertial navigation, the process of navigating via the use of measurements of rotations and accelerations, the sensors currently used drift over time, resulting in reduced accuracy unless they are regularly calibrated with GNSS.

Quantum sensors have the potential to overcome these limitations, due to their low drift and high accuracy. Quantum sensors of interest in navigation include quantum accelerometers, quantum gyroscopes, quantum clocks, quantum magnetometers, and quantum gravity sensors. By incorporating the new generation of quantum sensors into navigation systems, improved performance in the absence of GNSS is expected, for example, when GNSS is denied through jamming or spoofing.

However, before the benefits of quantum sensors can be realised in a navigation system, there are several challenges that need to be overcome in the sensors themselves, including improving their robustness and reducing their size, weight, power consumption, and cost.

In addition to the challenges in developing the sensors themselves, there are a number of challenges which need to be overcome in the integration of the sensors [10] [11] [12], including the data fusion of quantum sensors with classical ones.

Quantum enhanced radar - application example

Radar surveillance is used in a number of applications and locations, including urban environments, for the radar surveillance of small objects in low- to medium-altitude airspace. The surveillance of targets includes the detection, tracking and identification of targets in the location or locations of interest. Other applications for radar surveillance include counter-drone surveillance, drone traffic management and agroecology.

However, in urban environments, weak targets (e.g. drones, birds) can be masked by phase noise introduced by the local oscillator used in radar systems, and this can fundamentally limit the radar sensitivity. Advances in quantum technologies offer a potential solution to this problem through the integration of quantum clocks as ultra-stable oscillators into radar systems.

It is expected that this will reduce signal noise, enabling radar systems to detect small, slow-moving objects such as drones at longer distances and in more cluttered environments. Further benefits of quantum clocks in radar systems are expected when incorporated into next-generation distributed radar systems, which will allow surveillance with greater coverage and increased ability to detect stealthy objects.

However, before quantum-enhanced distributed radar systems can be realised, there are several challenges which need to be overcome in the clocks themselves, including improving the robustness, and reducing their size, weight, power consumption and cost.

In addition, there are challenges in how best to integrate quantum clocks into distributed radar systems, including, for example, how to distribute the new levels of timing accuracy without reducing its quality.

References:

[9] Economics, London. "The economic impact on the UK of a disruption to GNSS." London Econ., London, UK, Tech. Rep., (2017).

[10] Cheiney, Pierrick, et al. "Navigation-compatible hybrid quantum accelerometer using a Kalman filter." Physical Review Applied 10.3 (2018): 034030 **https://doi.org/10.1103/PhysRevApplied.10.034030**

[11] Wang, Xuezhi, et al. "Improving measurement performance via fusion of classical and quantum accelerometers." The Journal of Navigation 76.1 (2023): 91-102 **https://doi.org/10.1017/S0373463322000637**

[12] Tennstedt, Benjamin, et al. "Atom strapdown: Toward integrated quantum inertial navigation systems." NAVIGATION: Journal of the Institute of Navigation 70.4 (2023). **https://doi.org/10.33012/navi.604**

What is systems engineering?

The International Council on Systems Engineering (INCOSE) defines systems engineering as “a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods” [13]. INCOSE defines a system as “a combination of interacting elements organized to achieve one or more stated purposes”.

To enable the engineering of complex systems, systems engineers use a variety of principles. For example, a key concept is that of the system boundaries. A system boundary is a line of demarcation between the system itself and its broader context: it divides what is part of the system from what is external to the system. The operating environment or context defines entities that interface with the system but are not within the system boundary.

This concept is illustrated in **Figure 1**. This definition of systems and their boundaries allows systems engineers to work across different scopes and, consequently, with different boundaries.

In this diagram, a distinction is made between the **logical boundary**, which defines the direct responsibility of the engineer, and the **analysis boundary**, which defines the space of what is beyond the engineer’s responsibility but still needs to be considered to carry out effective product or system development.

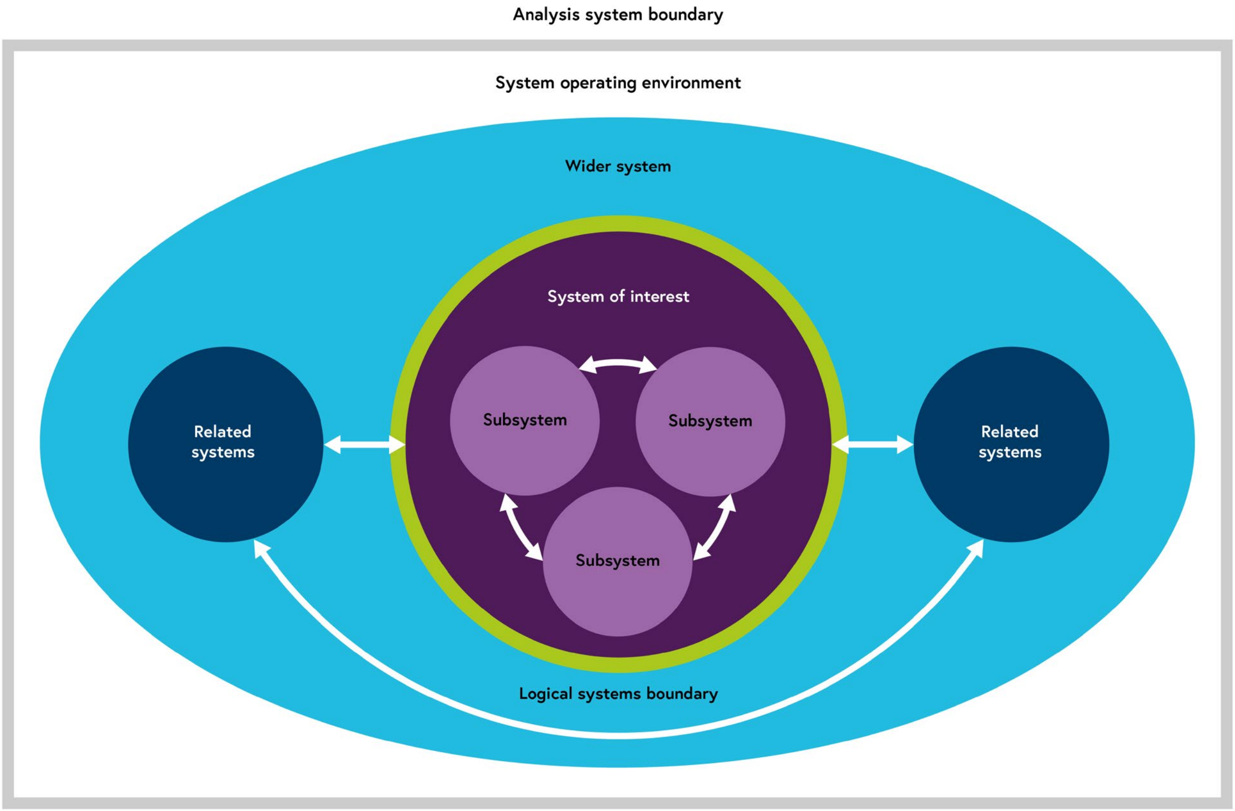

Figure 1: System boundary concept. Showing a system of interest, with internal and external interfaces shown as arrows.

References:
[13] INCOSE Systems Engineering Handbook, “A guide for system life cycle processes and activities”, Fourth Edition, INCOSE-TP-2003-002-04, Jan. (2015).

A specific life cycle model might be used to engineer a system like that shown in **Figure 1**. The most common model for this is often referred to as the 'V-diagram' as shown in **Figure 2**. This shows the sequence of different stages of the systems engineering process and how they are related.

It should be noted that whilst this is the most common approach, others exist and can be categorised as either linear, incremental or evolutionary models. The usefulness of such techniques is not restricted to being used for physical systems but also for systems of systems and services.

It is through the use of these techniques that systems engineering has been used to create things on all scales ranging from microscopic to macroscopic, from creating magnetic artificial cilia with cobalt nanoparticles [14] to building the International Space Station [15].

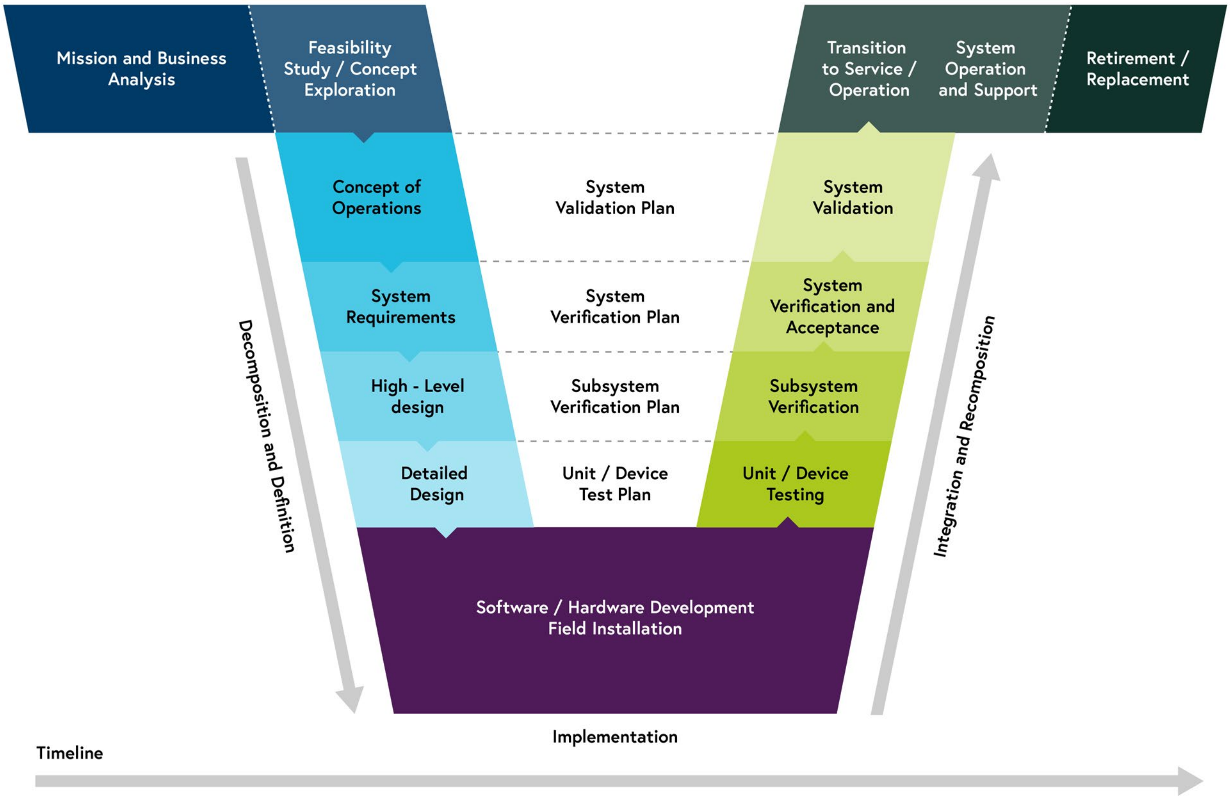

Figure 2.

Systems engineering methodology (V-diagram). The V-diagram shows all stages of the systems engineering process starting with identifying the concept and requirements, through to design, development and then on to integration, verification and validation. It is through the use of models such as these that systems engineers are able to effectively manage the life cycle of a system.

Note: It should be noted that the V-diagram can be used both as a wiring diagram (defining dependencies between processes) and as a lifecycle model (a linear interpretation of progression through lifecycle processes).

References:

[14] Benkoski, Jason J., et al. "Systems engineering at the nanoscale." Micro-and Nanotechnology Sensors, Systems, and Applications IV. Vol. 8373. SPIE, (2012).
[15] Stockman, Bill, Joe Boyle, and John Bacon. "International space station systems engineering case study." (2010).

Challenges in the application of systems engineering to quantum technologies

The nature of quantum technology is broad and ranges from quantum random number generators based on quantum states of light to quantum gravity sensors based on clouds of laser-cooled atoms. The nature of these individual systems themselves will affect the nature of the challenges posed to systems engineering.

In general, when constructing classical systems containing quantum technologies, they can be split into two categories, depending on how pervasive the quantum effects are across the system as a whole:

- **Quantum enhanced**
- **Quantum enabled**

For example, in the context of quantum communications, one can consider the following:

Quantum enhanced communications

Quantum-enhanced communications systems include applications where a quantum component has been substituted for a classical one, with the quantum effects being contained within the quantum component itself; the effects on the wider system are more akin to existing technologies.

For example, in the case where a Rydberg atom [note 1] based receiver is used as an alternative to a classical antenna, quantum effects would be confined within the Rydberg subsystem. In this case, quantum effects are localised and need only be considered within a small subset of the overall system architecture.

Note: Rydberg atoms are atoms that have one or more electrons, which have been excited such that the electrons are far from the nucleus, on average. Consequently, Rydberg atoms have a number of interesting properties including high sensitivity to electric fields, and the ability to be tuned to discrete frequencies over a very broad spectrum.

Quantum enabled communications

In contrast to a quantum-enhanced system, a quantum-enabled system is fundamentally based on quantum principles. An example of such a system would be a future quantum information network based on entanglement and teleportation effects. In this case, the entire system is underpinned by quantum effects. From a systems engineering standpoint, these effects will pervade the entire system leading to more far-reaching consequences.

It is expected that out of these two cases, the quantum-enabled systems will pose a greater challenge to existing systems engineering methods. Some of the quantum effects that pose a challenge to conventional systems engineering techniques are summarised in **Table 1** overleaf.

More information on the quantum effects listed in this table can be found in references [16] and [17].

References:
[16] Griffiths, David J., and Darrell F. Schroeter. Introduction to quantum mechanics Cambridge University Press, 2019.
[17] Fox, Anthony Mark. Quantum optics: an introduction. Vol. 15. Oxford University Press, 2006.

Table 1: Examples of quantum effects that will challenge systems engineering methodology. This table is not intended to represent a comprehensive list but rather to provide some examples of such effects.

Quantum effort or property	Challenge	Potential impact	Potential solution
Non-determinism	Quantum systems are inherently non-deterministic, meaning that the precise outcomes of measurements cannot be predicted; it is only possible to predict the probabilities of different outcomes.	This will pose numerous challenges to the engineering of such systems, including their verification and validation unless specific measures are taken to minimise their consideration or consequences.	Employ modelling and simulation which is stochastic in nature.
Entanglement	The presence of entanglement in a quantum system will lead to non-local effects which will not be encountered in classical systems.	Although the effects of entanglement are powerful and offer new possibilities in terms of systems performance, especially in terms of quantum computing and quantum networks, they constrain the ability to define or impose formal system boundaries (through their effects permeating traditional boundaries).	Careful consideration of individual components or sub-systems in isolation since entanglement effects will span beyond such distinctions.
Fragility of quantum states (decoherence)	Quantum states are fragile since any interaction with the outside world that leads to measurement will destroy the coherence of the quantum state.	The fragility of quantum states in terms of the ease with which they may be destroyed or coherence lost is another aspect of quantum systems that is likely to require novel systems engineering techniques. This may be especially challenging for systems modelling, which may require new techniques to deal with state multiplicity and fragility.	Systems engineering strategies such as isolation and containment could be used to deal with such effects.
State space explosion	The state space of a quantum system scales exponentially with the size of the system.	This means that an exhaustive test of all the possible states of the system rapidly becomes infeasible, which poses a significant challenge to system verification as well as broader modelling and analysis activities. This is a particular challenge for high-integrity applications where certification is likely to be underpinned by rigorous testing requirements. Similar challenges will need to be addressed in systems engineering, e.g., the adoption of artificial intelligence (AI).	Consider system state space from a hierarchical perspective (e.g. Harel's state charts).
Non-cloning theorem	Quantum information cannot be copied in the same way as classical information.	The inability to clone information will prevent the ability to monitor the internal state of a system or to audit its behaviour at a later date. This is likely to be a significant issue for high-integrity applications.	This will impose additional constraints on the design of systems that exploit quantum technologies.

Some possible means of addressing these challenges include:

- **Compartmentalisation** - designing the architecture of the system in a sufficiently modular way
- **Isolation** - designing facilities into the system so that quantum sub-systems or components can be verified independently of the other parts of the system and their characteristics are self-contained.

Another challenge which affects the systems engineering of new and novel technologies, including quantum technologies, is the lack of suitable specialised models.

Until these are developed, the systems engineering of quantum systems will be generally more challenging. For example, within quantum systems, system execution cannot be recorded at run-time. This could be a challenge for assurance since traditional methods to audit the system's performance may not be possible.

Systems engineering and the exploitation of novel technologies

Systems engineering is an extensive technical field that not only sets out established practice but also provides guidance on how particular domains should be addressed and particular technologies included. This guidance includes the introduction of novel and disruptive technologies and the considerations that need to be addressed with these, where special measures may need to be adopted in order to ensure that they are successfully integrated into the wider system [18]. Whilst software is an increasingly dominant technology 'substrate' in many systems, other substrates may be incorporated and exploited in systems using systems engineering.

Such systems engineering guidance could result in a number of strategies being devised to incorporate and exploit quantum technologies. These strategies should seek to isolate or contain quantum-specific considerations from standard systems considerations at the macroscopic scale, should they be sufficiently different. This methodology would be particularly appropriate for quantum-enhanced systems where the quantum component is limited.

For example, a quantum sensor may be treated as a delicate instrument with appropriate interfacing and protection. Such an approach ensures that it can operate effectively and that any quantum effects are contained within that component in the system. Adopting this approach should allow the use of established systems engineering technologies to be continued as far as possible, with new techniques being required only for the quantum aspects of the systems and their interfaces.

Isolation and containment form a fundamental overall strategy for hybridising technologies including those that are quantum-based with those that aren't - and the engineering associated with those technologies and the systems engineering which 'spans' them. This has yet to be widely done for systems that include quantum technologies. Therefore, the challenge here will be in applying this methodology to quantum systems that have a large number of distinct features that need to be taken into consideration.

For example, one of these distinct features is the minute scale of quantum phenomena. Quantum effects typically occur on scales on the order of 10-8 m to 10-16 m. Therefore, models used for macro-scale engineering will need to be made compatible with models of quantum phenomena.

This is not a unique problem and is an active area of research in other fields such as systems engineering of nanotechnology [19], but it has yet to be fully resolved.

Implications for requirements capture

Requirements capture is the result of engagement with users and other stakeholders in order to codify what the system needs to do and also what it needs to be. Requirements are important not only for recording the desired properties of the system, but also providing a means by which the final system can be contracted for, verified, and validated.

Requirements sets usually comprise both functional and non-functional requirements, which specify what the system **must do** and what it **must be**, respectively. Non-functional requirements typically relate to properties such as safety, security and reliability, for example.

Stakeholder requirements should be as far as possible solution-agnostic, however in reality the technology which will be used to provide a solution to the end users' needs will often influence the form of requirements that should be stated. Quantum technologies will be no exception here.

References:

[18] INCOSE, ed. INCOSE systems engineering handbook. John Wiley & Sons, (2023).

[19] Darrin, M. Ann Garrison, and Janet L. Barth, eds. Systems engineering for microscale and nanoscale technologies. CRC Press, (2011).

For example, the most significant change could be a recognition that quantum technologies may exist that may enable the system to meet user requirements that have been excluded previously. As such using exploratory prototyping in development may help refine requirements for more novel quantum systems. The lack of widely used predictive models for quantum systems may pose a challenge in identifying the suitability of quantum solutions to a given requirements set. The effects of quantum technology on system requirements, however, will be much more impactful and require careful consideration. This will affect both functional requirements (due to potentially altered causation) and non-functional requirements (due to different characteristics).

Implications for system boundary analysis

For quantum-enhanced systems, system boundary analysis will be more akin to existing systems engineering methods than for quantum-enabled systems.

For example, in a quantum-enabled system where entanglement is present, the identification of the system boundary will become considerably more challenging. In particular, entanglement has the potential for information to flow around the system outside defined interfaces which will make a reductionist or "divide and conquer" approach less effective. Consequently, new strategies will need to be devised to accommodate quantum technologies.

New strategies may entail working with multiple system boundaries, for example:

- one in which quantum effects dominate,
- one in which quantum effects are effectively contained,
- and a further zone in which some but not all quantum effects will need
  to be taken into account and will necessarily influence the style and scope of (systems) engineering that needs to be undertaken.

Implications for assurance and verification and validation

Verification and validation (V&V) is concerned with ensuring that the system that has been engineered satisfies the original requirements and stakeholder needs. For more sophisticated systems, especially those that are considered to be safety critical, this may lead to system certification, which will generally involve ensuring that the system is compliant with appropriate standards by organisations such as BSI or ISO/IEC, or defence standards, etc.

The V&V of quantum systems will be challenging as a result of the following four properties of quantum systems:

1. **The observer effect:** As with all systems, there is a need to design for tests; however, in the case of quantum technologies, certain tests will be impossible to carry out in practice. Due to the observer effect, measuring a quantum property can destroy it and render the measurement pointless. To address this problem, measurements will need to be conducted differently. For example, the system can be measured before being put into a quantum state and then after the quantum process has taken place to check consistency. Consequently, it is harder to build verification at all levels of the system in question.
2. **Lack of determinism:** At a fundamental level, the elements of a quantum system will not behave in a predictable manner, as is the case with their classical counterparts; research in systems engineering is considering the stochastic behaviour of systems due to the introduction of AI, and this may have applicability to quantum systems.
3. **The presence of entanglement:** Which leads to non-local phenomena and an ambiguous system boundary; will be more commonplace in quantum-enabled systems
4. **State space explosion:** The exponential growth of the dimensionality of the state space of a quantum system will mean the use of V&V techniques based on exhaustive searches are unlikely to be feasible. This could include exhaustive testing approaches as well as methods based on applying logic such as formal methods. While this is a problem for quantum technologies, it is not unique to them. Artificial intelligence-based technologies pose a similar challenge to system modelling, analysis and verification. In particular, the system's capacity to learn exponentially increases the state space of the system. This effect also poses serious challenges to the verification of such systems, especially those that are to be used for high-integrity applications where safety and security are vital.

The nature and severity of the challenges posed by these four properties will also differ depending on the granularity of the V&V testing activity that is being considered. It is likely to be the case for some systems (e.g. optically pumped magnetometers) that quantum effects are more observable at the unit or component testing level as opposed to on a larger scale when the system has been integrated.

The presence of quantum effects will also likely lead to the presence of new failure modes that will need to be both identified and have mitigating strategies devised and adopted. This will include analysis at the quantum component level and combining the findings from such consideration with a similar analysis at the system level.

There are trends in several engineering areas (particularly in security engineering) to rely more strongly on ongoing evidence rather than 'done and dusted' approaches to V&V because this contributes to improved agility and responsiveness. Unless suitably robust methods for the assurance of quantum technologies can be developed, this could become a sticking point in the adoption of such technologies. One route to achieving this could be through carrying out DevOps with quantum system developers working closely with system integrators and test and evaluation experts.

Implications for reliability engineering

The purpose of reliability engineering is to ensure that the resulting system has the required reliability characteristics. The reliability of a system is inherently non-deterministic and is therefore analysed using statistical/probabilistic methods.

Quantum systems are likely to pose additional challenges for reliability engineering due to the potentially large number of failure modes, the use of entanglement, the decoherence of quantum states and the potentially non-deterministic nature of the components that comprise the system. It is, therefore, likely that new forms of analysis will be required to understand such properties and engineer them for reliability.

The containment of quantum effects: maximising the use of conventional systems engineering methodology

If conventional systems engineering methodologies are to be retained, then approaches and mechanisms for incorporating quantum technologies need to be devised and codified.

Systems engineering of quantum-based systems may need to be developed as a specific discipline in its own right; this would allow quantum technologies to be integrated into wider systems while allowing conventional systems engineering to be retained as far as possible.

The challenges are, therefore, twofold: (i) how to successfully engineer the quantum aspects of the systems and (ii) how to interface these with the remainder of the system consisting of more conventional technology substrates such as IT.

This principle is shown conceptually in **Figure 3** for quantum-enhanced and quantum-enabled communication systems.

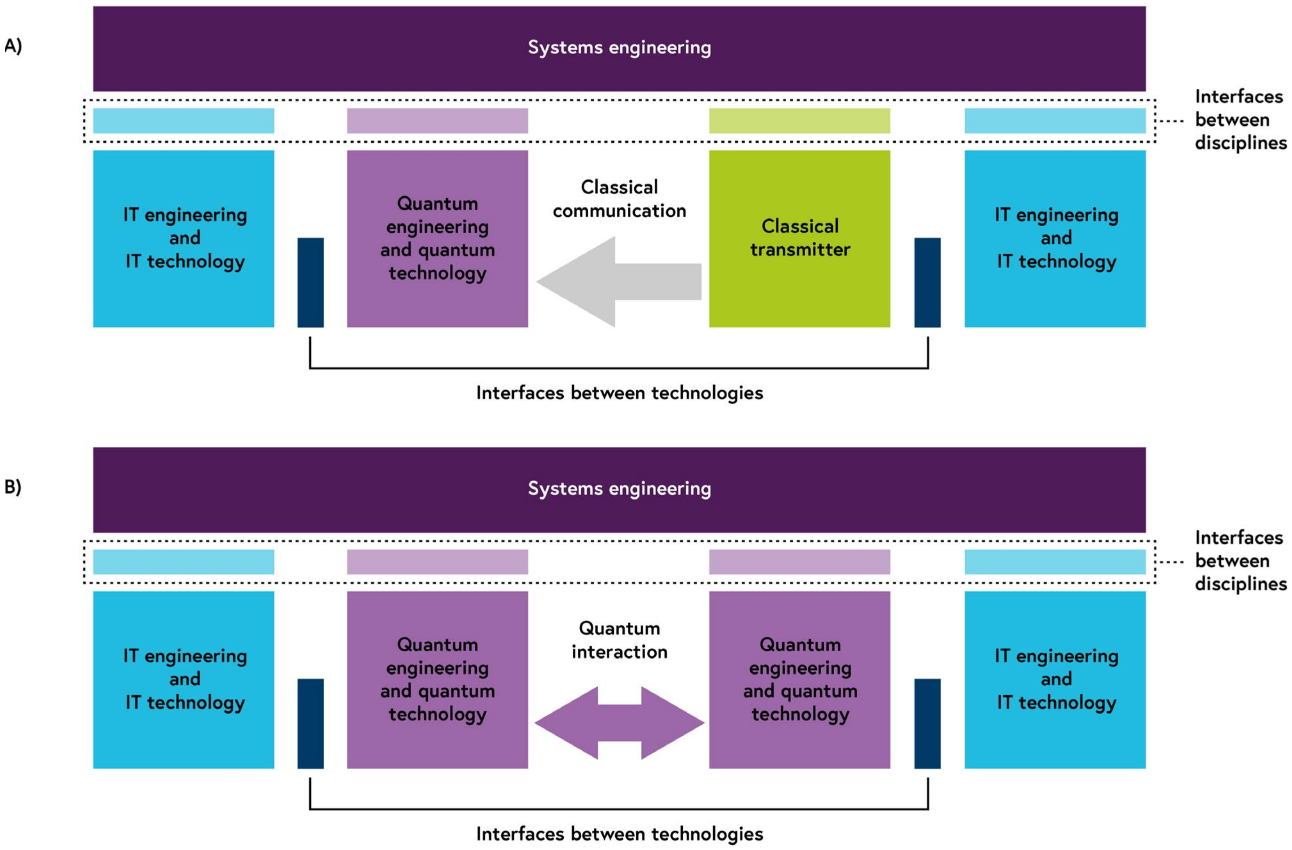

Figure 3

Examples of how interfacing could be handled in a communication system containing quantum technologies to integrate with conventional systems engineering. Indicated are places where interfacing between technologies and disciplines is required. The interfacing between quantum and other quantum or classical systems currently require development. (A) The interfaces for a quantum enhanced communications system, using a quantum receiver (B) The interfaces for a quantum enabled communications system.

A mapping is described below in **Table 2** that shows the impact of quantum technologies on different stages of the systems engineering lifecycle according to the terminology that has been defined above.

Table 2: Quantum influence on lifecycle processes. The nature of the quantum system will determine how much of an impact there is on each lifecycle process, with some quantum systems likely to have very little impact, while others much greater on the specific process in question. For example quantum clocks are expected to pose less of an integration challenge than quantum computers into existing systems.

Life cycle processes	Potential impact on engineering		
	Little to no impact	Some impact	Greatly impacted
System concept formulation and definition	x		
Stakeholder requirements	x		
System requirements	x	x	x
Systems architecture definition	x		
Quantum System/component specification and design			x
Classical System/component specification and design	x	x	
Quantum component development			x
Classical component development	x	x	
Implementation	x	x	x
Quantum Component testing			x
Classical Component testing	x		
Integration	x	x	x
Verification and validation	x	x	x

Challenges and potential solutions

While quantum technology is posed to make great strides in our ability to communicate, compute and sense, it is essential to understand how to incorporate quantum technologies into existing capabilities.

Quantum effects will pose substantial challenges to successfully engineering systems underpinned by quantum technologies and sub-systems. It is clear that to overcome these challenges successfully, a combination of technical and non-technical solutions will need to be considered.

It is suggested that some of the characteristics of quantum technologies challenge the conventional systems engineering paradigm, and if traditional systems engineering is to be largely retained, then approaches and mechanisms for incorporating quantum need to be devised and codified.

A new discipline of quantum (system) engineering may need to be developed as a specific discipline in its own right.

The interfacing between these disciplines will also need to be addressed.

Technical solutions

A number of technical measures can be adopted to overcome some of the challenges which have been described above:

- Methods to limit the effect of quantum technologies on the broader system.
- The development of library of standard quantum architectures that can be re-used will be valuable in assisting the development of quantum systems. This would build on existing systems engineering methods; for example, where possible, reference architectures and templates are used to facilitate the re-use of solutions to common problems. These would enable singular solutions to be applied to a range of such issues, though addressing these for the first time may be non-trivial.
- The development of accurate and practical models that can be used to predict the performance of quantum components. The absence of such models is not a systems engineering problem in itself but will pose an additional challenge to effective systems engineering.
- Further development of standard systems engineering tools and methodologies designed to help the development of technologies with low technology readiness levels [20].

In terms of overcoming the V&V challenge, systems based on quantum technologies need to be developed and designed so that they can be qualified and certified for use with minimal overhead. Excessive difficulties in such areas are likely to hamper the successful adoption of such technologies, especially in those applications where high integrity is required.

More broadly, some of the challenges quantum technologies poses are also being replicated in other fields where novel technologies are being deployed. One example which has been mentioned earlier in this paper is the “state space explosion” problem: this leads to an exponential growth of the dimensionality of the system’s state space, leading to challenges in system analysis, modelling and testing; this is also a challenge for artificial intelligence-based systems.

In short, quantum technology is not the only field potentially challenging for established systems engineering approaches. Novel systems engineering approaches are being considered that will address some of these challenges, including more rigorous stochastic model approaches. By working across disciplines, it may be possible to identify systems engineering approaches that could solve problems encountered when developing quantum systems.

References:

[20] Jones, Susannah. “Enhancing technology readiness assessment: The Engineering Severity Level Methodology and the Technical Readiness Level+ classification.” IEEE Open Journal of Systems Engineering (2024).

Non-technical solutions

In terms of identifying solutions to the challenges that have been highlighted, solutions lie not only in the technology itself. Solutions lie also in building appropriate communities and ecosystems with the requisite mix of skills and backgrounds to allow meaningful progress to be achieved.

The IRDS (International Roadmap for Devices and Systems [Note 1]) could be a helpful model to replicate in achieving this. The mix of skills required is likely to comprise systems engineering, quantum physics, and device-level engineering (e.g. optics, electronics and other underpinning components).

These are likely to be drawn from a number of organisations including government departments [Note 2], academia, research laboratories (e.g. The National Physics Laboratory) and the spectrum of industry from small start-ups and spin-outs through to the larger end-user/systems integrator companies.

An important aspect of this is ensuring that those with different backgrounds are able to communicate effectively when discussing technical matters. For example, a business case to convince an end-user of the merits of a particular technology needs to be structured and presented in a very different manner to an academic presentation to a scientific audience.

The adoption of consistent and well-understood terminology is also essential. Additionally, the engineering documentation produced will need to be usable by engineers drawn from different disciplines. There are a number of methods this could be achieved, including conferences, workshops and government-funded projects.

Professional bodies (e.g. The Institution of Engineering and Technology and the Institute of Physics) could also play a role in enabling these interactions.

Notes:
[1] Details of its successor can be found at **https://irds.ieee.org/**
[2] For example Ministry of Defence (MOD) and UK Research and Innovation (UKRI).

Organisational solutions

Professional body working groups are essential for the sharing of knowledge and best practice, and this would be an appropriate action for the Institution of Engineering and Technology (IET), Institute of Physics (IOP) or the Royal Academy of Engineering (RAEng).

This paper will be a useful starting point in such a dialogue and can be used as a platform to start considering the standing up of such groups.

Skills

New training opportunities will be needed in order to train practitioners across all levels of education, including those who have the higher levels (e.g. PhD), the middle levels (e.g. Masters Degrees, Undergraduate degrees) and those without. New training opportunities will ensure that future quantum technologists are equipped with the necessary skills for the engineering of these systems.

The existing Centres for Doctoral Training are a good first step in addressing this but typically focus on quantum technologies themselves as opposed to the wider systems implications and system engineering methodologies.

However, more work is needed to embed the required skill sets in the relevant communities (e.g., systems engineers, quantum engineers, and quantum scientists).

Training in the systems engineering of quantum-based systems would need to consider the following topics:

- Engineering techniques to contain or minimise the impact of quantum effects on the wider system
- Interfacing with and between quantum technologies
- Designing techniques to harness quantum effects in order to allow the system to meet the specified requirements

The authoring of clear, accessible and instructive texts on the subject would also be invaluable. These materials will need to be tailored to the respective target audiences, in particular a "one size fits all" approach is unlikely to be appropriate.

Other activities such as conferences, workshops and summer schools could also be utilised to ensure that there is quantum literacy among systems engineers and systems engineering literacy among quantum scientists and engineers.

A quantum technologies systems engineering community should also be established in order to allow those with common interests to share knowledge and best practices on this topic.

This is effectively a new technical discipline, so its relationship with other technical disciplines needs to be understood. The development of a body of knowledge (BoK), similar to what exists for conventional systems engineering and cyber systems, would be appropriate and would be another vehicle for disseminating best practice.

There are various aspects to professionalization, including, for example, corporate bodies of knowledge, handbooks, and standards. For systems engineering, these exist and would need to be updated in order to reflect best practices when dealing with systems underpinned by quantum technologies.

It would also be appropriate to review project organisational structures when developing quantum systems, in order to ensure that best practice is encouraged. This is because conventional project structures [Note 3] may no longer be appropriate when engineering systems underpinned by quantum technologies.

Further work also needs to be done to inform senior management (particularly at the c-suite level) to enable them to understand the potential benefits of quantum technologies and enable them to act upon the presented opportunities.

In a survey of engineering skills, 54% of engineering employers surveyed do not feel that senior management understands emerging technologies such as quantum (**iet-skills-for-a-digital-future-summary.pdf (theiet.org)**).

Notes:
[3] Often organised into algorithms, hardware, software and systems.

Regulations and standards

The existence and adoption of appropriate standards is an important step towards the development and adoption of new technologies. Activity in developing standards for quantum technologies is now increasing [21] [22]. Much of this is being driven by the US and China who are especially dominant in the areas of quantum computing and communications.

Although at an early stage, organisations such as BSI and CENELEC are already exploring the development of standards related to quantum technologies. The European Quantum Industry Consortium (QuIC) also has a Working Group which is looking at standards for quantum technologies.

There are options for standardisation that may need to be considered depending upon the sensitivity of the technology. For example, the UK Ministry of Defence has a hierarchy of standards that suggests bodies that can be used for a given application. These include ISO/IEC, BSI and CENLEC, OMG, and IEEE.

As part of the efforts towards standardisation, there needs to be some discourse on what topics should be addressed in an international forum and what should be addressed in other forums. This is especially important now we are entering a more competitive international phase in the development of quantum technologies.

References:
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[22] Van Deventer, Oskar, et al. "Towards European standards for quantum technologies." EPJ Quantum Technology 9.1 (2022): 33. **https://doi.org/10.1140/epjqt/s40507-022-00150-1.**

Conclusions and recommendations

Quantum technologies are currently starting to emerge from research laboratories and into the real world. Once commercialised they are poised to make a significant impact on society, ranging from improved communication in challenging environments to improved covertness.

These advances are expected to lead to a significant impact on the economy - for example, via the UK government's National Quantum Strategy Missions [23], which set out strategic challenges where quantum technologies will make a tangible difference.

Systems engineering will need to accommodate quantum technology as a new technology substrate, and whilst the approaches being proposed will reduce the impact on systems engineering, it is likely that there will be some modification required to it.

More significantly, a new engineering discipline will need to be developed concerning the engineering of technologies employing and exploiting quantum effects.

Without this, it will be a struggle to turn the promise of quantum technologies into well-engineered products that achieve the UK Quantum Strategy's aims. As the National Quantum Technologies Programme continues to develop quantum technologies and drive them towards commercialisation, systems engineering of quantum-based systems needs to be developed as an enabling discipline.

Consequently, the following activities are recommended:

Make quantum systems engineering a new discipline and build a community of interest.

The UK already has a strong background in systems engineering and is a global leader in developing quantum technologies (ranked 2nd for number of quantum companies).

However, what will make the UK stand out globally in the future and potentially demonstrate international technical leadership is its strength in bringing both quantum and systems engineering together. Systems engineering is critical to ensure new technologies integrate seamlessly into the existing environment, whether physical or digital, without unforeseen effects.

This is particularly the case for quantum, as it can have non-local effects. Systems engineering can mitigate this through effective planning and strategies such as compartmentalisation to help contain the quantum effects of the wider system. This would aid in the validation and regulation of the wider product and help to address some of the regulatory challenges.

By building a community of Interest in this field, best practices can be developed and shared as the discipline develops.

Improve quantum literacy

For the UK to continue to be a key player in the field of quantum technology, there needs to be greater quantum literacy within the industry, particularly at the C-suite level, to understand what opportunities the technology presents to their business.

Quantum technologies can improve accuracy and increase efficacy and efficiency in projects, which will result in a range of untapped potential to improve businesses.

In a survey of engineering skills, 54% of engineering employers surveyed do not feel that senior management understands emerging technologies such as quantum (**iet-skills-for-a-digital-future-summary.pdf (theiet.org)**).

References:
[23] https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions.

Focus on reskilling and upskilling in industry in readiness to adopt new technology

The UK is going to require skills in quantum at a range of levels (from PhD to technician) and across different industries. Already, employers say that a digital skills gap is harming productivity (49%) and restricting growth (35%) without the emergence of new technology such as quantum (**iet-skills-for-a-digital-future-summary.pdf (theiet.org)**).

Specific skills are needed in quantum systems engineering to enable the use and integration of new quantum technologies into mixed quantum/classical systems. Through repurposing unused apprenticeship levy funding, for example, SMEs can be supported to increase their skills in this area and ensure that the full supply chain can prepare for its effects.

Regulation

Quantum will require a new approach to regulation as it is inherently hard to replicate and predict and can have non-local effects in a system. Government and regulators should use the 2024 Regulation of Quantum Technology Applications report by the Regulatory Horizons Council as a basis for further discussion.

Going forward, regulators should expand on this and focus on the systems element of regulation in this field.

This is an opportunity for the UK to take a leadership position in global regulation and standards for quantum technology.

Systems thinking in future planning projects

Further support is needed to engineer solutions to the unique challenges that quantum faces through systems engineering. Systems thinking should be embedded at an early stage in the development of new quantum technologies, and support should be given to the development of new approaches to combined quantum and classic systems.

Good practice in systems architecture for quantum technology should be shared to increase the pace of development and regulatory approval.

Quantum catapult hub that draws from expertise across other catapults and has a primary focus on systems engineering and working with industry

Establish a quantum systems engineering hub between the existing catapults to oversee standardisation, sharing of systems architecture and best practice, in addition to supporting appropriate regulation in this space.

This would however need a strong link to industry, particularly working with SME's and system integrators to improve quantum throughout the supply chain.

Continue to implement the National Quantum Strategy and associated funding to prevent the UK from falling behind as an international competitor

By continuing to fund work that allows companies and universities to work together across the value chain, the UK's quantum ecosystem can be further strengthened, linking up component manufacturers, quantum system developers, systems integrators, and end users.

Of particular importance is ensuring funding for future Contracts for Innovation (previously known as the Small Business Research Initiative or SBRI), which enables larger companies such as systems integrators to work more easily with quantum SMEs.

Glossary of terminology and terms

No-cloning theorem

The no-cloning theorem states that it is impossible to create an identical copy of an arbitrary unknown quantum state.

State space

A state space is the set of all possible states of a system.

Quantum decoherence

Quantum decoherence is the loss of quantum coherence. Which is to say a quantum state returns to a classical state.

Quantum entanglement

Quantum entanglement is when two or more particles are generated, interacting, or sharing spatial proximity in such a way that the quantum state of each particle cannot be described independently from the others.

Quantum system

A quantum system, such as a quantum clock, whose primary function is to generate a quantum state and utilise this state for a purpose (E.g. magnetic field sensing).

Systems which utilise quantum technologies

These are systems which are designed to perform a function and merely use a quantum system as a subsystem to achieve the overall objective (e.g. a navigation system).

Qubit

A qubit is the basic unit of quantum information and can exist in superpositions of the |0› and |1› states. Qubits are analogous to classical bits used in classical computers.

Authors

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Rob Atkins (QinetiQ), Robert Patching (L3Harris), Sophie Mears (PA Consulting), Mark Everitt (Loughborough University), Kieran Bjergstrom (Loughborough University), Susannah Jones (Dstl), Rosie Sloane (Dstl), Matthew Ball (Thales), Michael Wale (UCL).

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References:

[24] Ministry of Defence's Science and Technology Portfolio, 23rd January 2023, **https://www.gov.uk/government/publications/defence-science-and-technology-programmes-and-projects**

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Richard is an applied physicist, leading PA's work in helping clients understand and demonstrate how emergent physics can enable new and differentiated capability that allows us to mitigate conventional engineering limits. Richard is the physics lead on PA's activities in Quantum Technologies, specific example including quantum sensing for RF applications and the use of quantum computing in creating decision support tools, including "the first piece of work to demonstrate quantum benefit" of quantum computing.

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Robert Hancock is a scientist in the Defence Science and Technology Laboratory, where he serves in a number of roles, including Chief Scientist for the Communications and Networks Programme; he is also the lead for Dstl's industry research into quantum communications. Prior to joining Dstl, he completed a PhD in particle physics, followed by nearly 30 years in industry, working in research, standardisation and product development for a variety of customers in the Defence, National Security and commercial sectors.

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David Harvey has over twenty years of experience working in defence research and has been with Thales since 2000 having worked for DERA/MOD prior to this. The majority of David's career has been in sensors, signal processing, mathematical modelling, algorithm development and systems engineering. David's main specialism is in sonar signal processing. David oversees Thales UK's activities in Quantum Technologies. David has a First Class MPhys degree in physics, is a Fellow of the Institute of Physics and holds an Adjunct Fellowship with the University of Southampton.

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