The challenges for Systems Engineers of non-classical quantum technologies

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(Dated: December 12, 2017)

Non-classical quantum technologies that rely on manipulation of quantum states and exploitation of quantum superposition and entanglement are approaching a level of maturity sufficient to contemplate commercialization as the basis of practical devices for sensing, communications, navigation and other applications in the relatively near-term. However, realization of such technologies is dependent upon the development of appropriate Quantum Systems Engineering (QSE) approaches. It is clear that whilst traditional systems engineering will support much of the integration need, there are aspects associated with system of interest definition, system modelling, and system verification where substantial advances in the systems engineering approach are required. This paper lays out in detail the challenges associated with Quantum Enabled Systems and Technologies (QEST) and analyses the adequacy of systems engineering processes and tools, as defined by the Systems and Software Engineering lifecycle standard (ISO/IEC/IEEE 15288), to meet these challenges. The conclusions of this paper provide an outline agenda for systems research in order to engineer QEST.

I. INTRODUCTION

Non-classically explainable aspects of quantum physics have been fundamental to the development of many modern day devices: semiconductors, the transistor, the laser, etc., underpin the development of the information (or digital) age in which we live. The application of quantum phenomena in almost all these technologies has been to improve upon classically familiar concepts such as Boolean algebra and the electronic switch (i.e. the transistor). Now however, we are at the dawn of a new era where state-of-the-art technology promises the ability to leverage quantum effects for the creation of new capabilities. Manipulation of the quantum state and specific exploitation of quantum superposition and entanglement may lead to capabilities such as sensing through walls, improved navigation (e.g. satellites), GPS-free navigation, more secure communication, and even quantum computing. These new devices will involve the creation and manipulation of a delicate macroscopic quantum state that is likely to require systems designers to have some understanding of the underlying physics as well as their engineering discipline, to harness the technologies’ intended capabilities. This new quantum revolution [1] has been well summarized by Pritchard and Till [2 3]; they originally used the term Quantum 2.0 to distinguish between mainly 20th Century technologies and those emerging from the most recent quantum physics research. This term can lead to ambiguities as usage is not standardized and so this paper will use the expression “Quantum Enhanced Systems & Technology(ies)” (QEST) to refer to systems that rely specifically on, or make use of, manipulation of quantum state, as described above. The first commercial devices exploiting these quantum properties are anticipated within the next few years; they are likely to be devices that interact with the environment in communication, sensing and imaging applications. QEST is, therefore, of interest to engineers who must turn science into workable, safe, and commercially viable products and systems. But implementation will only be possible if certain new engineering problems, unique to systems reliant on quantum coherence, can be overcome. These include new types of interfaces and new insights into the concept of a system’s boundary, the critical significance of interactions between quantum systems and the environment in which they must operate, the current lack of suitable engineering models, and the lack of verification (test and evaluation) methods for such systems. It is clear that new engineering approaches will be needed in order to realize the potential of QEST.

Translating the results achieved within physics laboratories into manufacturable, safe, and commercially viable devices and systems will be a substantial engineering challenge. Successful implementations will only be possible if certain new engineering problems, unique to systems that are reliant on manipulating macroscopic quantum states, are addressed. Systems Engineers (whose role is to integrate the contributions from many other disciplines), in particular, must address the challenge of creating systems that exploit new effects not previously encountered and obeying new, but as yet, undefined design rules [4]. In this paper, we shall introduce the challenges for Quantum Systems Engineering (QSE), explore the areas in which development of systems engineering is required and set forth some possible approaches that will enable the development of QEST. In doing so, we are cognizant of the distinction that must
be drawn between the practices of early adopters and the later established processes for maturing and matured technologies. As Christensen has established, “disruptive technologies typically are first commercialized in emerging or insignificant markets” [5] and it is rarely in the interests of established organizations to invest aggressively in disruptive technologies. Our main purpose is to look forward to longer-term development of QSE and recognize that a “lighter touch” of systems engineering will be appropriate for early adopters. Nevertheless, the systems thinking approach will also be essential for early adopters in the task of transitioning from laboratory to real-world application.

Most systems organizations use the ISO/IEC/IEEE 15288 standard, “Systems and Software Engineering – System Life Cycle Processes” [3] to define the processes used in the development and support of complex systems. The purpose of the standard is to support projects and organizations in the acquisition and supply of systems. As such, it provides a comprehensive overview of cradle-to-grave systems management, and so this standard is used as an analysis framework, through which we identify the process areas in which QEST quantum phenomena must be considered, and the types of methods and tools that will be required to support the engineers charged with developing the systems. The use of the standard as an analysis framework leads to the identification of gaps in knowledge and the concomitant research needs for systems engineering.

It is always the case that the lifecycle must be tailored to the particular project at hand; Annex A of the standard [3] discusses this aspect. Tailoring takes account of both organizational needs and project-specific features; it results in the adoption of particular processes and tools for, and intensity of, systems engineering.

To begin, we must agree a definition of what we mean by a system and the important properties with which the systems engineer deals. “A system is a combination of interacting elements organized to achieve one or more stated purposes” [6]. Thus, a system has elements (which may refer to parts, components or sub-systems); relationships between those elements; and a purpose. The relationships can be thought of as conduits along which material, energy, or information is transported from one element to another [7], and these must be organized such that an emergent behavior will result (i.e. one that cannot be achieved by any of the elements acting in isolation, but only as a result of interactions between elements). In the case of engineered systems, we speak of them having an “operational purpose” which satisfies the need of a customer, operator, or of society in general, and a “functional purpose”, which is essentially what the systems must actually “do” to meet that need [8].

In addition to the System of Interest (SOI, see below), there are so-called enabling systems that are required to support the SOI in its functions. Examples could include environment, control systems, maintenance systems, training, etc. [6]; these have a particular significance for QSE as we shall discuss below.

Systems Engineering is the “interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations, and constraints into a solution and to support that solution throughout its life” [6]. Systems Engineers must, therefore, concern themselves with the interests of stakeholders and all the contributing disciplines to a system: their job is to plan and manage integration.

Maturity of technologies are often assessed using Technology Readiness Levels (TRLs) that range from “basic principles observed and reported” at level 1 to “actual system proven through successful mission operation” at level 9 [9]. It is worth noting that integration is a part of the activity required to achieve each of levels 5, 6, 7, 8, and 9, and so Systems Engineering can be considered to be the key aspect of achieving operational readiness for a new technology [10]. However, it is important to note the findings of Honour [11], that investment in systems engineering early in the lifecycle (i.e. low TRL) is most significant in terms of project success. It is for this reason that the Quantum Technologies community has an opportunity to truly benefit from early adoption of Systems Thinking and Engineering.

Allhoff et. al. [12] commented that “it is sometimes very easy to get caught up in what is scientifically possible and ignore the engineering problems that come with it.” The purpose of this paper is to signpost the practical engineering considerations for development of QEST devices. It starts with a description of QEST and then develops the modern day challenges of defining a system of interest and how QEST may affect that. A description of the way in which ISO/IEC/IEEE 15288 should be used and tailored follows as an introduction to a section by section analysis of the relevant technical processes that QSE must consider. Through consideration of current QEST application projects (in the defense domain), we examine specific challenges associated with development from TRL 3 to TRL 7. Drawing together the threads of these various analyses, we conclude with recommendations concerning how QSE should be developed in order to realize the amazing possibilities that QEST offers to society.

II. NON-CLASSICAL QUANTUM TECHNOLOGIES

Many technologies of the electronic age, and latterly the information age, rely on quantum mechanics to explain and optimize their operation. Developed in the early 20th Century, Quantum Mechanics was a departure from classical physics that was concerned with understanding light (photons), matter (atoms) and their interactions. Thus, the operation of semiconductors, lasers, and a host of familiar technologies can be described using the mathematics associated with quantum mechanics. Pritchard and Till [2] have referred to this as the first
quantum revolution, arguing that we are on the brink of a second quantum revolution (QEST) in which devices actively create and manipulate quantum states either to improve upon existing capabilities or to deliver fundamentally new solutions. New technologies will be enabled by directly exploiting the subtle quantum effects of quantum entanglement, superposition, and tunneling. These effects will potentially enable extraordinary advances in applications such as precision timing (clocks), communications, sensing, computing, and many others.

A. Subtle Quantum Effects QEST

Quantum Superposition: encapsulated in the famous analogy of Schrödinger’s cat, the principle of superposition is that an object exists simultaneously in more than one possible state – and for cat states these are macroscopically distinguishable. Such superpositions can be used to advantage in information processing and metrology, and coherently manipulated. They persist until we try to measure the state (at which point superposition ceases) or environmental effects destroy them (indeed it is their sensitivity to environmental effects that can make quantum objects potentially excellent sensors). Superposition implies that an object can be in more than one place, or have more than one value of an internal variable. Through super-cooling, scientists have achieved quantum states in visible objects. This effect is pertinent to some types of sensor and quantum computing.

Quantum Entanglement: is a specific form of superposition between distinct physical systems and concerns the deeper than classical correlation of the state of the system (such as position, momentum, polarization and spin) of objects often separated widely in space and/or time. Thus, measurement of one object will define another, even though no information has been exchanged. Entanglement has been demonstrated for objects as large as small diamonds. This effect is pertinent to communications and quantum computing.

B. Applications

It is helpful to summarize the likely applications that will be enabled by QEST. These are applications that are currently the focus of research and development programmes, but at varying levels of maturity[2]. Most of these applications represent technology push, in the sense that QEST may provide an opportunity to improve an existing capability (faster, more accurate, etc.), but as experience is gained, it is likely that entirely new capabilities (as yet unconceived) may be created.

Precision timing is significant for many applications, examples include Global Navigation Satellite Systems (GNSS), financial networks and trading, communications systems, satellite monitoring and ground-based navigation (through GNSS), and electrical power grids. However, atomic clocks that use existing technologies can already achieve accuracies of $2 \times 10^{-16}$, at which level the effect of variations in the local gravity vector have an observable effect in accordance with general relativity. Finding an application, outside the national standards laboratories, that can exploit an improvement of 2 orders of magnitude from a new generation of quantum clocks may be difficult; perhaps counter-intuitively, the value of the new technology may be that it makes possible a smaller or lower power solution for applications that have less demanding timekeeping requirements.

In the area of secure communications, Quantum Key Distribution (QKD) is an important application of entanglement. Point-to-point QKD is already available, but development of networks is still experimental and there are also technical challenges with practical devices associated with range and room temperature for free space operation; arguably, now is exactly the time to adopt QSE in order to address such challenges. Furthermore, QKD is still vulnerable to man-on-the-side attacks if the attacker can achieve a timing advantage.

Many advances are anticipated in the area of sensors, with QEST effects offering elegant systems solutions for sensing through walls, detection of hidden materials or deep underground voids, quantum radar to detect stealth objects, and ghost imaging. No enabling operators to see round corners. Entanglement may enable biometric sensors that work at the sub-cellular level, but without causing damage. Quantum technologies offer the possibility of several orders of magnitude improvements in sensitivity for the measurement of electric and magnetic fields.

Further (but less mature) areas for development include navigation using the local gravitational environment (GPS-free!), gravity imaging for scene analysis, and detection of movement of massive objects. Rotation sensors of 2 nrad/s/Hz$^{-\frac{1}{2}}$ sensitivity will offer benefits, including: inertial navigation, roll stabilisation, image stabilization, various vehicle (e.g. UAV) controls, spacecraft guidance and survey systems.

Quantum computers were proposed around 1980 and work differently to traditional binary electronic computers. Potentially, they offer (for some algorithms) an exponential improvement in computational speed over conventional computers for some specific forms of calculation that are important in cryptography and search algorithms, and significantly lower power demands. Predictions vary for when a viable machine for general use will be available, but IBM have announced their intention to construct commercial IBM Q systems with ~50 qubits in the next few years.

III. PRACTICAL IMPLICATIONS FOR ENGINEERING QEST

There are a number of engineering challenges associated with development of the applications to exploit
QEST. Firstly, there is the problem of maintaining fragile quantum states over extended timescales and distances; this problem is explored below through considerations of current QEST application research and development in the defense domain, though the problems are domain-independent.

Secondly, there are problems of scale and scalability. Whilst these problems are not unique to QEST, they are also discussed, because they must also be overcome in order to realize practical QEST devices.

A. QEST Integration Implications, based on current development projects

The appeal of QEST devices as sensors is their sensitivity to environmental effects which allows the user to infer specific values with high precision. However, a fundamental issue is the difficulty in isolating a single environmental effect, whilst mitigating the coupling effect to all other environmental factors, which may degrade the functionality of QEST.

1. Implications

As stated above, a “A system is a combination of interacting elements organized to achieve one or more stated purposes” [6]. A quantum experiment within a laboratory environment can be considered as a functioning isolated system, as it has operational elements and/or sub-systems working together in order to achieve a purpose. In this case, the purpose is to demonstrate the proof of concept of a system (i.e. TRL 3 [9]).

Commonly, these elements are a combination of non-classical technologies, such as lasers and quantum states, driven by classical devices, such as power supplies, amplifiers, etc., which are typically not constrained by size, weight or power requirements. To ensure that the system meets its purpose it is operated by highly trained physicists within a laboratory: this reduces the chance of interactions between operating elements and real world environmental effects.

The developmental step from quantum experiment to QEST prototype (TRL 4) is non-trivial, as the system’s purpose has to evolve from proof of concept of an experiment, to proof that the system has a real world (by which we mean to imply an environment outside an experimental laboratory) operational and functional capability. This imposes loose constraints on the system’s size, resulting in a set of operational elements that integrate together within a confined volume.

Sensing and time keeping QESTs require cold atoms (100 μK) that can be manipulated into a functioning quantum state. This requires periods of cooling and state preparation, prior to state evolution, where an atomic state is allowed to couple to an environmental effect. The sensitivity of the QEST is dependent on the precision to which these processes are carried out. Stray magnetic fields, generated by driving operational elements that interfere with these processes pose a substantial risk to the functionality of QEST. Therefore, care is needed when integrating classical devices, such as ion pumps (which generate magnetic fields), with non-classical elements to preserve quantum states, in order to reduce sympathetic interactions and parasitic effects [22]. Within a laboratory environment Mu-metals are used around areas of quantum state preparation to diminish this effect. However, this increases the weight and volume of a system and may inhibit deployment in real-world systems. Quantum Technology Shielding is an important area of current research [29].

Integrated non-classical driving devices within a QEST can induce a host of additional undesirable features such as resonant vibrational frequencies and thermal gradients, all of which can reduce the QEST functionality and even result in permanent damage to the system, if left unmitigated.

The next major step in the development of a QEST device is proof-of-principle that the system fulfils its functional and operational purpose within its intended environment (TRL 5). With regards to QEST, the original device is required to operate on a platform [24] subjected to real world environments. Thus, the QEST device must be integrated as a sub-system of a platform system such that desirable emergent behaviors of the platform with QEST will result.

Many of the same issues overcome in developing the laboratory QEST prototype are apparent in real world environments following systems integration, except, it is now the platform and its subsystems that contribute undesirable features, such as temperature gradients, electromagnetic interference, vibrations and acoustic noise. There is also the added complexity that the QEST prototype is now constrained in size and weight by the platform and installation. Above all, the QEST device must integrate with the platform without interfering with other subsystems; for some platforms, this could have safety implications.

Cold atom inertial sensor advancements [25] have highlighted the potential to overcome current navigation sensor issues; specifically those related to inertial navigation bias instability and drift, related to Global Navigation Satellite System (GNSS) [26] [27]. However, the technology is currently hindered by the tradeoff between interrogation time, coherency of quantum state and dead time [28].

Initial prototype testing of an inertial sensor in a micro gravity airplane flight has indicated the feasibility of a QEST atom-based gravimeter [29] [30]. However, platform vibration levels (10^-2 g Hz^−1/2), variations in acceleration (0 – 1.8 g), rotation rates (5°s^−1) and systematic uncertainty from time-varying magnetic fields present significant challenges. In addition to this, separate investigations have found that radio communication systems on board a test flight resulted in interference
with the QEST laser stabilization [30].

Submariners could benefit significantly from QEST navigation devices [25], however they are one of the most hostile working environments known today and immature on-board systems could lead to a catastrophic loss of life. Consequently, there are numerous limiting factors to consider when integrating QEST devices into this type of environment.

A few well known examples of the predominant factors that could reduce QEST functionality are:

- thermal variations within an enclosed vessel,
- size restrictions,
- limitations of Radio Frequency (RF) emissions, and
- weight restrictions imposed in order to achieve the correct buoyancy.

However, a case study carried out by the Chartered Institution of Building Services Engineers (CIBSE) [31], highlights several new limiting factors that are relatively unknown:

- variance of air pressure, which can be 25% above and below atmospheric pressure,
- onboard ventilation, which can result in large variations in concentration of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and hydrogen (H_2),

To overcome the size and weight limiting factors, current active areas of research are developing chip scale QEST [32, 33] and portable laser systems [33, 34]. However, the variance in air pressure and environmental gases could still pose a significant risk to the functionality of the technology and requires further investigation.

From just a few examples it is apparent that for early QEST devices, stepping out of the laboratory to real world environments (TRL 4 to 5) is arguably one of the most challenging tasks in the near future and the early adoption of systems engineering approaches is likely to ease this transition.

An aspect of systems integration that will enable greater understanding of the trade-off between sensing superiority and engineering limitations, and illuminate the overall QEST integration challenge, is to develop an approach to integration of prototype QEST within existing platform sub-systems, rather than as deployment of completed platform sub-systems. Such an approach would pose significant new challenges, but offers the prospect of high payoff. It is envisaged that this will become an active area of research within the next few years and could form the next development step in meeting platform operational time and reliability requirements [TRL 6 and 7].

B. Scale Implications

Models for macro-scale engineering must be combined with models of phenomena that occur at relative scales of the order of 10^8 to 10^16. The physics is necessarily different, but phenomena at vastly different scales must somehow be accommodated. With many applications, laboratory demonstration is not proven to be scalable to practical devices and so new models are required to understand the scalability issues. This has been discussed by Papadakis from the perspective of systems engineering micro- and nanoscale devices [35] and focuses on the consideration of changes in the behavior of continuous variables (material and fluidic properties) and those that give rise to quantized behavior, but mainly drawing attention to the need for quantum mechanics to explain certain phenomena. In terms of the impact of scale on systems engineering, Sample [36] has drawn attention to the variability in batches of nanomaterials, having implications for integration and asserting the need for standardization. She noted, in particular, that higher failure rates might be anticipated and this certainly has implications for the reliability aspects of systems engineering. However, Breidenich [37] has focused on interfaces as being a critical issue for Systems Engineering of micro and nanotechnologies, because the variation in scale adds considerably to the complexity of defining interfaces.

So far, although scale is recognized as a major issue for systems engineering, there are no definitive views on how it should be dealt with in general. This is an area of systems engineering research with significant implications for the practical realization of QEST devices and systems.

C. System of Interest (SOI)

In order to design, develop, or update a system, it is essential (for philosophical, technical and commercial reasons) to define the system clearly. [7] describe the ‘Narrow System of Interest’ (NSOI) as those elements of the system directly under the control of the engineer; the ‘Wider System of Interest’ (WSOI) as those elements of which the engineer must take account, but which are not directly under the engineer’s control; the ‘Environment’ that provides context for the SOI; and the ‘Wider Environment’ that has no influence at all on the system (see Figure 1). They also discuss the ‘Meta System’ which could be considered as the organizational and technical system used to build or develop the NSOI. For simple systems, the NSOI can be defined in a straightforward manner as the elements that the system contains; the analysis for this is referred to as ‘structured system identification’. For complex systems, ‘behavioral systems identification’ is a more appropriate approach, in which the interactions of interest are identified. The engineer must clearly classify the elements of a system as within NSOI, WSOI, environment, or wider environment in order to understand...
how the elements should be treated.

In recent times, increases in technology system complexity and significant increases in connectivity has led to difficulties in identifying the NSOI. Systems of Systems (SoS) considerations mean that many different properties must be taken into account [38] and the dynamic nature of systems (in which connections appear and disappear) must be represented somehow in the definition of the system [39].

The subtle quantum effects described in section II.A introduce non-traditional interactions that generate significant problems in distinguishing between NSOI and WSOI and may, furthermore, bring elements of what may have previously been considered as environment into the SOI. For instance, when measuring the rotation of a platform, one must also consider the rotation of the earth; also, when measuring gravity (wider environment), one must account for local environmental movement. For quantum systems, interactions with the environment are very significant because they can destroy the quantum states that allow QEST behaviors within microseconds. Quantum systems that use entanglement to achieve their purpose will need to somehow include the entangled objects within the NSOI, but it is not clear how this should be done. For instance, moving entangled atoms around “components” in an atomic computer challenges the usual notion of system boundaries and design methodologies.

Furthermore, the coupling between enabling systems and the NSOI may also lead to ambiguity in definition of the systems boundary. For instance, the system to laser cool and trap atoms for certain applications [40] could be regarded as an enabling system and, therefore, in the WSOI. However, in practice this may require development within the overall application and thus fall within the NSOI. For experiments in the laboratory, this is not an issue, but for practical, commercial devices, this becomes an important consideration for costs and workflow.

The SOI is conceptual and its articulation by a systems engineer reflects the how they understand the system. For complex systems, explicit definition of the SOI is the means through which co-workers may develop a shared understanding. Whether explicitly stated, or simply implied, the SOI defines what the developer includes in models of the system, which has a direct bearing on how the system is understood. In practice, a systems engineering team will be able to reach an agreement about the SOI for QEST, but there is clearly a need for principles to be developed to enable a consistent and meaningful approach to definition of SOI for QEST.

D. Challenges

To summarize, quantum systems engineering must consider:

- Integration of nanotechnology and other non-conventional technologies (such as low temperature or ultra-high vacuum) due to properties of the materials [36]
- Multi-scale issues, especially concerning the combination of models from vastly different scales [35], which makes partitioning and interface specification challenging
- System identification with reference to the challenges of subtle QEST effects and to the multi-scale issues above
- Scalability in terms of expanding experimental technologies to practical devices: it is not a foregone conclusion that effects will scale in a straightforward manner, or at all
- Emergence such that decomposition and analysis of a system may not enable overall behavior to be predicted at all [42]. This is a basic problem of the complexity of the systems and the scientific uncertainty of the quantum interactions
- Interface specification: related to the emergence problem and the multi-scale issue above, specifying interfaces to include QEST effects and, perhaps more particularly, understanding where the interfaces occur between different systems, or different components, will be a significant challenge
- Device size, robustness and environment: for many potential applications the associated enabling systems (e.g. cooling systems) are of substantial size and the environmental demands are challenging. Furthermore, precision alignment of components means that robustness in non-laboratory environments is demanding. This means that integration into practical environments (e.g. an airplane) will require technological advances
- Design approach: Systems Engineering is traditionally thought of a top-down approach (although...
frequently bottom-up also occurs); related to the multi-scale issue identified above is the need to combine a top-down and bottom-up approach to design [43]. Also, if the systems engineering community is to identify additional applications for QEST it will need to do considerable ‘bottom-up’ modelling to be able to identify and articulate the benefits that could be realized from early adoption of QEST for each application considered.

Although several of the issues above have been considered elsewhere, there are so far no definitive systems engineering approaches that have been identified. However, the subtle QEST effects have so far received little attention from the systems engineering point of view and this will be the main focus of the analysis below.

Although out of scope for this paper, it would be remiss not to mention that QEST will rely on the availability of metals such as rubidium, and the reliability of supply in a congested, contested, and competitive world may become a critical issue for future exploitation of QEST (see for example: [44]). Thus one might anticipate that end-of-life and re-use processes could become a significant part of QSE.

IV. ISO 15288

The ISO 15288 standard [6] assumes that a typical system life cycle includes the following stages: concept, development, production, utilization, support and retirement. Of course, utilization and support are generally considered to run concurrently. However, the standard makes no assumptions about the development life cycle structure, which is chosen by engineers to suit the type of systems development being addressed. The standard is written mainly from a project perspective and clusters processes within four categories: agreement processes are concerned with acquisition; organizational project-enabling processes are mainly concerned with responsibilities and resources; Technology management processes are concerned with planning, decisions, risk, and information management. Technical processes are concerned with the engineering aspects for system development, sustainment, and disposal; it is within this category that the special considerations for QEST occur. In all system development, the life cycle must be tailored to the particular system of concern: this includes the structure of the life cycle stages, the processes and decision gates within those stages. In the sub-sections below, we consider particular processes (identified by name and clause number from the 2015(E) issue of the standard) for which QEST considerations should be included. This paper provides guidance to the systems engineer to where life cycle tailoring should include specific QEST implications. The development of systems that exploit QEST is likely to go through several maturity phases within a short space of time and so it is important to recognize that the systems engineering methods, processes and algorithms will also need to develop in line with the maturing levels of quantum integration.

Some familiarity with ISO/IEC/IEEE 15288 will be beneficial to understanding these sub-sections. It should be assumed that clauses not listed below have not, at this time, been identified as requiring special consideration in QSE.

A. Stakeholder needs/requirements definition (clause 6.4.2)

That the system exploits QEST effects might be a System Non-Functional Requirement [45] for a demonstrator device, but it ought not to be assumed that QEST is the “answer” per se. A crucial part of these processes will be to establish the critical performance requirements and measures, such that it is possible to decide whether QEST offers effective benefit over other (more conventional) technologies. Similarly, the requirements for enabling systems must be established, although it is possible that these will only emerge after substantial design work. The acceptability of the enabling systems (size, cost, capabilities) must be established as early as possible to determine the viability of using quantum technologies within the application under consideration. Thus far, there is no specific difference for QSE, but definition of the down-select criteria in order to prioritize customer requirements and assess feasibility is a crucial step for quantum, because many of the factors may currently be unknown or, at least, uncertain. Until more is known about the practicalities of implementation, the definition of down-selection must be carefully constructed to ensure that relevant parameters are measurable and provide sufficient information for decisions to be made.

To some extent, it could be argued that research in quantum systems falls into the “technology push” class of innovation (i.e. that the systems provide opportunities for invention of new capabilities), whereas stakeholder requirements management is predicated on the notion that stakeholders already know the capabilities they need and wish suppliers to create appropriate systems to deliver those capabilities. Currently the type of benefits that quantum systems may provide is insufficiently defined. Thus, quantum systems may not be considered if existing techniques will satisfy the need, particularly given that the technical risks of using them may be high, although this may be different for early adopters, as noted in section I. Research and the anticipated effort to exploit quantum systems over the next few years will provide the knowledge needed to define requirements appropriately for quantum systems to be considered in the solution space. Furthermore, various demonstration programs being funded around the world will develop the skills, experience, industrial capabilities and embryonic supply chains that will provide the essential infrastructure necessary for quantum systems to be considered in the solution space.
An example of how quantum technology can provide an unexpected benefit emerged during the work of one of the authors with the geophysics industry. Initial discussions established that the sensitivity of the quantum gravity sensors that are becoming available does not provide sufficient advantage for users to justify the cost and risk of moving from the conventional systems that they currently use. However, when the discussion explored the tasks that the geophysics industry was undertaking, rather than focusing upon the sensitivity of the sensor, it became apparent that the rapid stabilization and ruggedness of the quantum sensors would provide a large benefit to the users. This was a benefit that could be quantified in terms of the time and cost to complete each task and thus it made QEST systems an attractive proposition for the industry.

In summary, the part of the stakeholder requirements processes need specific consideration is the tailoring of the down select criteria to ensure that appropriate distinctions between QEST and non-QEST solutions can be made, and thus quantum benefits are not overlooked.

B. Systems requirements definition process (clause 6.4.3)

This process transforms the stakeholder requirements into a set of (technical) system requirements that a proposed solution must meet. The resulting systems requirements cover functional, non-functional, performance, process, and interface aspects, and include design constraints. However, ‘they should not imply a specific implementation’ [6] and herein lies a dilemma: the use of QEST effects implies a set of constraints not present with other implementations (e.g. management of entanglement, temperature limitations for some technologies, size implications for the whole system). There will also be intrinsic requirements concerned with interference or non-interference due to QEST effects. Enabling systems will also be defined at this stage.

Techniques such as Quality Function Deployment (QFD) may be employed at this stage: this comprises a set of linked matrices that begin with the stakeholder wants and needs and potential technical responses (Matrix 1). Through a system of scoring appropriateness of the technical response to the stakeholder need and the correlation of various elements of the technical responses, the system requirements are gradually developed. New matrices are added starting from the outcome of the first to add increasing detail to the technical response. The rules around the successive matrices vary from one author to another or, more importantly, one project to another. Cohen [46] has provided a variety of possible definitions of the matrix of matrices (i.e. linked set) that address different challenges. [45] has considered four QFD phases as shown in Figure 2; if one considers the phases to be iterative, rather than strictly flow down (which may be practically true in many projects), and one retains several potential technical responses at the earlier stages, then one may explore the overall solution requirements, bearing in mind, for instance, that manufacturing requirements may demand changes in the earlier stages for practical reasons. The difficulty with this approach for QEST is that a) the appropriate models for analysis of technical requirements are immature, because of multi-scale problems and b) a corollary of this is that emergence is not properly predicted because of the decomposition process itself. Although QFD is not the only technique that may be used, it is a popular and effective tool that illustrates some of the challenges associated with the systems requirements definition process.

The challenges may be partially resolved by development of a top-down meets bottom-up approach, but the main lack is adequate models of the potential systems to provide reliable correlation between the elements of the technical responses.

An outcome from an NPL workshop on quantum timing, sensing, and navigation [47] was that a family of models is required. A system model to provide both industry and academia with a basic tool to predict the system performance that, in principle, could be achieved with the new generation of sensors in different system configurations. A detailed system model or simulation that is based on the engineering reality and can therefore provide realistic estimates of likely performance for a first generation system employing quantum sensors. This model or simulation is an essential prerequisite for significant investment in developing and demonstrating a real system.

Definition of design constraints due to QEST effects may also prove problematic due to model limitations.

In summary, tailoring of the systems requirements definition process should adopt a top-down/bottom-up hybrid approach. A major issue for these processes is the adequacy of the models used to establish the relationships and correlations between different technical requirements and this will only be resolved through the development
of better multi-scale models that properly account for QEST effects (see section V).

C. Architecture definition process (clause 6.4.4)

Because a key outcome of architecture definition is the traceability of the architectural elements to stakeholder and system requirements, the competence of the architecture definition process clearly has a dependency on resolution of the issues identified in the previous two sub-sections. Basically, architecture can be thought of as the ‘organization of resources’ [48], but the incorporation of QEST effects within those resources may require new approaches to the definition of the properties, characteristics, functions and constraints allocated to the architectural elements. This will require Quantum Systems Architects to reach a consensus and establish standard representations for QEST entities. These will also be applicable to the design definition processes discussed in the next section. The degree to which new types of entity are introduced at the architecture level is dependent, of course, on the level of abstraction that is needed, and this is not yet clear. The functional architecture is unlikely to be affected by the introduction of QEST, although specific functions within that architecture may be new.

There are, however, some architecting principles that should be borne in mind. Quantum technologies are expected to advance rapidly during the next few years, as such, one can anticipate the need to upgrade and improve systems frequently until reliable and stable patterns emerge for specific applications. Architecting is a key element of system life cycle planning, and the principle of modular architecting will be very important. These processes include the assessment of candidate architectures, which is an immature area within systems engineering [49], although developing. The assessment should prioritize the competence of the modularity for enabling frequent insertion of new technology. To support the Quantum community, the adoption of open architectures (which, simply expressed, means that they are published in sufficient detail for developers to reliably interface their systems to other systems) should be encouraged [49].

Definition of system of interest and interfaces will be problematic for system architecting (see section III.C). Interfaces to the enabling systems and the specification of enabling systems will require particular attention. It is usual for interfaces to be specified in an Interface Control Document (ICD) [50], although it could be a reference model rather than a document. A standard template is usually employed for the ICD in a particular domain and so an ICD template that includes quantum-related aspects of the interface is required.

The physical architecture will need to take into account the precision and interaction requirements of the Quantum technologies. As before, the key issue with this is the adequacy of the multi-scale models for defining these interactions.

In summary, community effort is needed to define standard representation of QEST architectural elements. ICD templates for systems employing quantum technologies are also required. Tailoring will require particular attention to assessment of candidate architectures that exhibit good modular and open characteristics. The physical architecture must take quantum interactions into account to avoid undesirable emergent behaviors.

D. Design definition process (clause 6.4.5)

Following from the architecture definition, the design definition processes provide sufficiently detailed information about the systems as a whole and the individual system elements to enable implementation [6]. The matters and issues identified for that architecture definition process are also included in this process. However, an important aspect of this process is the selection of the technologies required for each system element. Essentially, the inclusion of QEST increases the trade space available to the engineer in making technology selection, but herein lies a challenge. There are a large number of trade space tools available, but as yet no commonly agreed set of models and processes [51]; often the application of such tools and their parametrization is proprietary, as this can be a significant component of a company’s commercial advantage. The development of suitable models and their incorporation into trade space decision support frameworks should be an area of intensive research effort in the future. Furthermore, the effectiveness of trade space analysis, even assuming the models are adequate, is highly dependent on choice and structuring of the attributes against which the trade is conducted. So far, little knowledge exists on how to structure the trade for inclusion of QEST technologies and, once again, the vastly different scales that are involved in practical devices means that multi-scale analysis will be a complication. Trade studies take place at various stages of the development life cycle, at different levels of detail. An important consideration for tailoring will be the appropriate level of quantum modelling that must be included at any particular stage of the development life cycle.

Standards are emerging for quantum technologies, particularly in the area of security, e.g. quantum cryptography [52] and quantum key distribution [53] from ETSI [54]; design must necessarily take account of these standards, but there is a need for additional standards as these technologies begin to be deployed in practical devices.

It is important to recognize that the individual system elements are likely to be developed by several or many different organizations. The processes must account for appropriate supply chain management, particularly during trade-off studies to ensure that designs are optimal and can be implemented as designed once production begins.
In summary, tailoring of the design definition process draws on the recommendations for architectural definition, together with use of enhanced trade-off tools that specifically take quantum effects into account. Standards are emerging that will assist the design process through constraints and interface specification. Trade-off studies involving the supply chain are already commonplace, but appropriate education of supply chain members in quantum technologies will be required.

E. System analysis process (clause 6.4.6)

At a stakeholder meeting for Quantum Systems Engineering held in 2015 [55], attendees were asked: how much quantum mechanics should engineers need to know to implement quantum technologies? Unsurprisingly, perhaps, industry representatives responded: “as little as possible.” The question remains unresolved, but it is the demands of the system analysis process that will determine the level of quantum mechanics knowledge that systems engineers require. More generally, the development of QSE techniques should be predicated on finding ways for a wide range of technical staff, with different specialist knowledge, to collaborate, and avoiding the need for most to have an in-depth understanding of QEST. Careful partitioning and the development of parametric models for the individual components are the usual first steps at the system level – some of the component level techniques – e.g. QFD – can provide a useful framework for enabling collaboration across the different skills and disciplines that are essential in developing and manufacturing a practicable QEST component. Clearly, quantum physics knowledge is required for the process of validating assumptions and results.

F. Implementation process (clause 6.4.7)

Conventionally, implementation refers to the development of system elements (ready for integration) that meet the requirements, architecture and design. It is not uncommon for implementation to introduce new constraints that must then be reflected back into requirements, etc. Crucial design features that enable delicate quantum effects will most likely be not subject to compromise, and so the process must include rules and tests to ensure that unwanted changes are not introduced. An example might be that even seemingly insignificant changes to a component could change the thermal paths for the whole system, destroying the quantum effects or leading to component failure. One can expect that, as in the case of integrated circuit design, which is driven by the ITRS [56] roadmap [57], (addressed at major international conferences of IRPS, ESREF and ICMAT and is supported by bespoke tools in the workflow), reliability will become a major area of research in quantum technologies. The principles derived from this research will inform the implementation strategies developed during the implementation process.

In summary, tailoring of the implementation process will require principles for reliability engineering to be incorporated. Testing implementation changes for their potential effect on the whole system will require modelling in advance of agreement to changes.

G. Integration process (clause 6.4.8)

Assuming the ICD (described in section IV.C) includes the information relevant to quantum systems, then the integration process should not be dissimilar to that for regular systems. Similarly to the implementation stage (IV.F), any constraints introduced during integration and the process must ensure that these do not affect quantum effects or system robustness. Integration must take place in an environment representative of the intended deployment environment to ensure that the system will interact appropriately with it.

A major challenge to the introduction of quantum technologies is the size, complexity, and (lack of) robustness of the systems and enabling systems. This is, however, a challenge for Quantum Systems research, rather than a change to process.

The application of an incremental development model [8] could be problematic, because of unpredicted emergent quantum behaviors during integration of new capabilities, but this model generally assumes that all the requirements are well-known in advance, so it is unlikely that this would be a likely choice of development model, especially for early adopters.

H. Verification process (clause 6.4.9)

Verification establishes that the system, or system element, fulfils its requirements and is built as it was designed. This is established through test. The difficulty for testing system elements is that the fragile states of QEST mean that measurement can be counterproductive. To carry out verification of elements, there is a need to design for test, but the tests themselves may be impossible to carry out in practice. To state it bluntly, because of the observer effect, there is no point in measuring a quantum property if that measurement destroys the property. Considering this problem at a more remote level of measurement, one could check consistency of input and output through some form of controlled experiment, but even then, it would not be possible to verify that the system had followed the algorithms that were intended (i.e. it may be possible to measure end states, but not intermediate states). It should be noted, though, that there is a large body of work on certified quantum non-demolition measurement that addresses this problem from the physics perspective (see for example: [58]).
The increase in the number of possible system states is also problematic, because testing must be affordable and time limited.

The interconnectedness and increasing levels of autonomy in modern systems are challenging conventional approaches to verification. To some extent, QEST simply adds to the difficult task of verifying complex and, often, non-deterministic systems. The tailoring of the verification process requires entirely new approaches to verification; some have argued that a new verification paradigm is required and work is underway to develop new tests for quantum systems to support verification e.g. the QuProCS project sponsored by the European Commission[59].

Verification takes place at each step of the systems development life cycle. When requirements are generated (see sections IVA/B) then a test that will determine whether the requirement has been met should be determined. This then becomes part of the test program of the overall verification plan. For many steps there will be no need for a different approach to verification, but there will be steps associated with system element that employ QEST and overall verification of the system, where testing will be hard to define.

In summary, tailoring the verification process could be the most intractable parts of the overall life cycle tailoring activity. This is in part due to system complexity and lack of deterministic behavior of highly connected systems, and in part due to potentially untestable states of the quantum system. Together with other systems communities, there could be a need for an entirely new verification paradigm, e.g. [60], though there is not yet agreement on what that paradigm might be.

I. Validation process (clause 6.4.11)

Perhaps because V&V is alliterative, validation is often considered to be part of the same process as verification, but in fact these are different processes that serve different purposes within the overall life cycle. Whereas verification is concerned with the correctness of the system in terms of compliance to design and ensuring that results of tests meet the expected results, based on system requirements, validation refers to checking that the system, once built, meets the stakeholder requirements (i.e. the business or mission objective). If the stakeholder requirements include a specific quantum requirement, then this could prove complicated to test, but it is unlikely that the requirements at the business or operational level would do so; thus, tailoring of the validation process is unlikely to include specific quantum aspects. For early adopters, the customer requirement is likely to evolve so that validation is complicated by not knowing what is actually required.

J. Maintenance process (clause 6.4.13)

The maintenance process will likely need to include monitoring of the quantum systems so that fault diagnosis is informed and, certainly in the case of early applications, knowledge of the system behavior relative to maintenance requirements can be established.

K. Disposal processes (clause 6.4.14)

The systems are likely to contain a number of high value components, but it is unlikely there will be additional considerations for disposal that are specific to quantum.

V. MODELS

The design of any advanced technological system requires a hierarchical family of models. The hierarchy is usually based on levels of abstraction, working from a high level model with little detail down to models which may contain thousands or millions of objects. In systems engineering the hierarchy of models can mimic, but is not necessarily equivalent to, the increasing detail associated with requirements analysis and specification. Scientists and engineers use models to represent aspects of the world for a variety of purposes [61], and in many engineering problems, the family of models will also include individual, discipline-specific models that may or may not be coupled, and which serve different purposes within the overall design activity.

For QSE the family of models will need to include, at least, a basic system model to provide both industry and academia with the means of predicting the system performance and behavior of a new generation device in different system configurations, and a detailed system model, based upon engineering reality, capable of providing realistic estimates of likely performance.

Focusing specifically on quantum devices, simulation of these can be split into several potentially overlapping, somewhat subjective categories:

i. Physically realistic models of the device and its quantum state (possibly including environmental effects, measurement, feedback and control). These may be quite sophisticated and realistic but, in the absence of a quantum computer to solve them, limited to relatively simple systems. Such models will usually be semi-analytic or entirely numerical. Indeed, to the best of our knowledge the Berkley Lab supercomputer boasts the world record of modelling 45 qubits (with a maximum of 49 simulatable). As a guide, if Moore’s law continues to hold, an extra qubit would be classically simulate-able every two years.

ii. There is a range of models that try to approximate the state of a subset of quantum systems including
many-body statistical methods and approximate methods treating quantum systems coupled to an environment of other quantum systems (open systems methods). While these models have a quantum nature to them they do have limitations; for example standard ways of modelling open quantum system require a number of approximations to be made to derive a dynamical model for the evolution of the system state (known of as a master equation). Here a number of choices need to be made that depend on motivation and which often carry subtle implications. For example, demanding conservation of probability (i.e. insisting on Lindblad form [62]) may lead to the introduction of non-physical additions to the model [63][64]. This approach is often acceptable, and sometimes the only one available, when seeking to understand the physics of an open system. However, the value contributed by these approximation methods has yet to be established.

iii. Quantum models that try to predict behavior of parameters, characteristics or outputs [65][66].

iv. Semi-classical and classical models that are similar in ambition to iii, but only in situations where the devices are not really behaving quantum mechanically.

v. Some exploration of hybrid models has been made that couple, for example, classical and quantum dynamics [67]. Such approaches have been used with limited success to model some hybrid quantum-classical composite systems. There are a number of ontological difficulties with these models which perhaps explains their limited use in the physics community and their predictive nature has yet to be established within the scope of a device engineering perspective.

One of the main motivations for pursuing quantum computing and simulation is to make possible computing tasks that are not merely beyond the reach of existing hardware but also beyond the reach of any foreseeable classical computing solution. Somewhat ironically this level of computational power is required to carry out quantum device design using some of the modelling techniques outlined above.

Clearly, there are open questions regarding the most suitable modelling choices for quantum effects, but these models must then be brought together with engineering models for system design. These may be architectural in nature, but the coupling with physics models is by no means defined. Capabilities analogous to the semiconductor community will be needed. In CMOS, quantum physics is used to characterize new transistor designs with models operating at atomic scales, but once a classical switch has been characterized, hierarchical modelling can then be used to enable full chip design [68]. Quantum systems are different; simulating one of any appreciable size can only be effectively done on a quantum computer (testament to this is the creativity that the quantum chemistry community has employed in developing useful models of molecular systems). It seems clear that the modelling solutions effectively deployed in areas such as CMOS are unlikely to become part of a systems engineering solution without some significant additional methods being developed. In CMOS systems, there is little physicality in the higher level models within the system - these are concerned with timing and system integration difficulties. These models are not phenomenological in the way that a physicist is used to thinking; as the physical implementation is below the level of abstraction, the models are more process-ological (to coin a phrase).

Giere has stated that models are used for a variety of purposes [61] and there is a danger, in developing engineering models that rely on those currently used by physicists, that the motivation (and purpose) in each discipline is different. Physicists seek to understand nature and test this understanding in laboratory experiments that may focus on precision within only a few experiments, whereas engineers are interested in developing a product that will need to be manufactured, maintained and operates with a cradle-to-the-grave mindset. As such the notions of model validity, correctness and fitness for purpose are different.

Simulation of quantum technologies is, unsurprisingly, one of the principal challenges of developing the hierarchical modelling systems engineering capabilities. It is needed to realize the kind of engineering design and system verification strategies effective in more established disciplines. This hierarchical notion of modelling has yet to be realized for quantum systems where it is not clear how quantum effects such as entanglement can be accounted for at higher levels of abstraction. As such this represents an area in need of significant research and development.

To summarize, there is an absence of modelling techniques for QEST design: models of quantum devices that currently exist are generally not established for any but the simplest configurations. The linkage between the physics models and engineering models that may be used to build design tools is also an area requiring significant research. The lack of suitable models is probably one of the most significant difficulties facing QSE, particularly as this impacts design, verification, and (possibly) validation parts of the system development life cycle.

VI. DISCUSSION

A. Identification of key knowledge gaps

Systems engineering combines systemic thinking (consideration of the system as a whole and its interaction with the environment) with systematic viewpoint (concerned with the parts of the system and how they interact) [69]. This paper is predicated on the assertion that a system engineering approach will be needed to transform experimental QEST into viable devices, where viable implies that they are sufficiently robust and reliable to be used for important endeavors and that the producers of such devices have a realistic commercial proposition. We have intentionally avoided making an assertion about the
intensity of the systems engineering approach that should be used, but have recognized that this will be somewhat different for early adopters (in the next few years) compared to the larger scale enterprises we anticipate once the QEST begin to mature as commercial systems.

ISO/IEC/IEEE 15288 [6] is the standard recognized by the systems engineering community as defining the process types for managing the whole lifecycle of a system. Using this as an analysis framework, we have essentially asked the questions:

- Does the capability currently exist to perform each technical process stage if the system under consideration contains QEST? If not, what are the capabilities that must be developed?

The approach taken to address the questions has been to assess current methods, as reported in the literature, and in the experience of the authors, to determine the extent to which it is likely to give a satisfactory outcome at each stage. Although this might be considered somewhat subjective, the purpose is to identify potential weaknesses that would arise using current methods within a systems engineering framework, rather than to rigorously determine failures in a quantitative fashion. Indeed, the potential weaknesses identified indicate that such a rigorous analysis is not yet possible. The outcome of this analysis is an agenda for research and development that will lead to the principles and methods for quantum systems engineering.

Where knowledge gaps have emerged, these are mostly not specific to the overall maturity stage of QEST.

The detailed discussion of the challenges associated with QEST at each process stage is summarized in Table 1.

It is clear that the most significant current deficiency is a lack of appropriate models through which QEST systems can be designed. However, the difficulty in defining a suitable SOI is a contributor to this problem, because without a consistent and reliable approach to definition of SOI, it is not possible to define a model, even if suitable modelling techniques are available. These two deficiencies, which are undoubtedly the most significant and most complex that must be addressed, are of a fundamental nature and must be investigated through collaboration between scientists and systems engineers.

Other deficiencies (e.g. new architectural representations, integration strategies, etc.) fall more naturally into the realm of pragmatic engineering development; these problems can be addressed starting from current practice. However, it is important to note that the pragmatic approach may only be possible once progress has been made on the fundamental aspects.

Of the process stages, it seems that verification is the most problematic: the measurement of intermediate states is prevented by physics. Thus the impact of this must be assessed and alternative approaches to verification developed if necessary. The other problem, of too many system states to test practically, is emerging in systems engineering more generally as a significant issue (see for e.g. [60]). There is emerging a major research area concerned with identifying new paradigms for verification.

### TABLE I. Summary of QEST Challenges for Technical Process Stages of ISO/IEC/IEEE 15288

| Process stage | Key issues for QEST |
|---------------|---------------------|
| A. Stakeholder requirements | Lack of suitable models for down selection of technological approach; Lack of criteria for down selection to include QEST options; At current maturity of QEST, it is unlikely that stakeholder requirements will be sufficiently detailed |
| B. Systems requirements definition | Lack of suitable models, leading to inability to adequately predict emergent behaviors |
| C. Architecture definition | New architectural entities and representations may be required for QEST (this is currently tractable); Evolvable architectures are required (this is currently tractable); Interface definition may currently be inadequate |
| D. Design definition | Lack of models for use in the trade space; Not currently clear how to construct trade space to include QEST |
| E. System analysis | Need to ensure partitioning of design enable specialists can collaborate without the need for in-depth QEST knowledge (should be currently tractable) |
| F. Implementation | Principles for reliability engineering must be included |
| G. Integration | Integration strategies must accommodate quantum effects to avoid robustness issues |
| H. Verification | Cannot measure intermediate states; Test plan cannot include all possible states (too many), implies need for new verification paradigm |
| I. Validation | Dependent on well-defined stakeholder requirements: this may not be possible for early adopter QEST devices |
| J. Maintenance | Suitable monitoring strategies need to be defined, but not yet clear at what level |
| K. Disposal | No issues identified |

#### B. A sense of proportion

On the one hand, the analysis above indicates significant problems to be overcome in order to systems engineer QEST, on the other hand, various in-depth analyses [13, 20] have forecast the delivery of viable QEST within the next few years. The resolution of this paradox is that systems engineering generally reduces cost, risk, and time in complex projects. Whilst the delivery of viable QEST is possible, in common with all disruptive technologies, the risks are comparatively high and success is
far from guaranteed. The near-term delivery of QEST will come from early adopters. Thus quantum systems engineers need to consider the techniques and processes that will enable the near-term delivery, whilst developing the methods and applications that will be needed to reach the initial maturity delivery of QEST in the medium term. The achievement of this objective is not only technical; it will also require development of the appropriate business models through which enterprises can assure commercial success.

VII. CONCLUSIONS

Systems engineering is an essential approach to the creation and continued use of complex systems. Non-Classical Quantum Technologies (QEST), which rely on manipulation of quantum states and exploitation of quantum superposition and entanglement, introduce new complexities that engineers have not had to deal with hitherto. However, the exciting new capabilities that QEST may enable, and the advances of quantum mechanics in recent years, suggest that we are on the brink of a quantum revolution and must prepare to transition exciting quantum science into viable engineered devices. Collaboration between quantum scientist and systems engineers is needed to develop the engineering processes and methods to realize the potential offered by QEST.

Using the Systems and Software Engineering - Systems Life Cycle Processes standard [11] as an analysis framework, we have analyzed the extent to which systems engineering processes can meet this challenge and identified a number of areas in which advances are necessary. At a fundamental level, there is a need for a consistent and reliable approach for defining the System of Interest (SOI) for QEST and there is a significant lack of appropriate models to enable many of the process stages. The important activity of system verification is unsuitable for QEST using current approaches and methods; it is suggested that an entirely new verification paradigm may be needed.

ACKNOWLEDGMENTS

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