Challenges to progress in control and readout electronics for quantum systems

Quantum information science and technology (QIST) systems rely on complex classical electronics to control and read out the quantum-based processor or component. These control and readout electronics comprise a wide range of digital and analog circuitry and components, operating in some cases in vacuum or at cryogenic temperatures, and have stringent performance requirements for quantum applications.

The control and readout of QIST systems requires the synthesis and detection of precise pulsed, static, and slowly varying analog signals. The performance of the quantum portion of the system depends sensitively on the properties of these signals, such as amplitude, frequency, phase, and signal-to-noise ratio. These properties should be stable and settable with high resolution, and typically need to be calibrated or fine-tuned periodically during operation. As a result, the electronics typically use high-performance digital-to-analog converters (DACs) to output signals and high-performance analog-to-digital converters (ADCs) to read in signals. High-speed digital electronics are required to drive these DACs and ADCs, and to enable low-latency feedback from inputs to outputs as appropriate. Some QIST systems also use spatial light modulators, cameras, and/or photon detectors for outputs and inputs. While these photonics technologies are outside the scope of this roadmap, all require high-performance digital drive electronics. Pulsed or time-dependent inputs and outputs for QIST systems must occur with deterministic timing, which is handled by the digital electronics and systems for time and frequency synchronization of multiple DACs, ADCs, and digital inputs and outputs. In some cases, high-performance absolute frequency references for the generated signals are also required. The number of output and input channels generally scales linearly with the size of the quantum portion of the system, implying that large-scale quantum systems require control electronics with a very large number of synchronized, deterministic, high-performance output and input channels.

The required instantaneous bandwidth of the analog input and output signals varies among quantum technologies, but for pulsed signals is typically between ~1 MHz and ~1 GHz. Some signals are used directly at baseband, while others are used to modulate carrier signals at microwave frequencies (up to ~10 GHz) or optical frequencies in the infrared, visible, or ultraviolet. Direct digital synthesis and direct digitization of modulated microwave signals, as opposed to analog up-conversion or down-conversion, are becoming increasingly common with advances in ultra-high-speed DACs and ADCs. This roadmap does not address modulators for optical signals, although the drive electronics for the modulation signals are considered.

In addition to the digital electronics, DACs, and ADCs mentioned above, control and readout signals rely on a broad range of active and passive electronic components for analog signals from dc to microwave frequencies. These include cables, connectors, filters, attenuators, circulators, mixers, couplers, splitters, amplifiers, modulators and demodulators, frequency multipliers, switches, and more. These components generally must exhibit high linearity, high stability, ultra-low noise (even down to the quantum limit of added noise at microwave frequencies in some instances), and various other properties depending on the specific application. In many cases, these components are used in vacuum and/or at cryogenic temperatures, including temperatures below 100 mK. In some instances, the necessary electronic components are not commercially available.

QED-C, in consultation with its members and other experts, identified the gaps and needs relating to control and readout electronics for quantum systems. These barriers to progress may be grouped into three overarching themes.

Theme 1: Scaling up. This theme focuses on the technological challenges related to scaling up control and readout electronics to enable larger quantum systems, such as quantum computers with thousands or millions of qubits, each of which must be separately controlled. The field is near the limits of what can be achieved by “just add more of the same” scaling. New technical innovations as well as improved engineering are necessary to support the desired scaling of quantum systems.

Theme 2: Quantum-specific characterization and validation. Most components and technologies used in control/readout electronics for QIST were designed and developed for other applications, and thus their ability to satisfy the often more stringent performance requirements specific to QIST applications is not always known or well characterized. This is the case for individual components as well as for larger integrated systems of control/readout electronics. The challenge of characterizing performance becomes harder as the systems scale up and become more integrated, as necessary to meet the needs identified in the first theme.

Theme 3: Workforce, market, supply chain, & policy needs. Ultimately, a strong industrial ecosystem for development and production of control and readout electronics is required to enable the production of large QIST systems. This theme focuses on the market, supply chain, and policy challenges to building the ecosystem. Some of the needs identified include quantum-relevant workforce training, trusted supply chains, balancing intellectual property protection with collaboration, and the challenges of potential export controls.

Theme #1: Technological challenges for scaling up quantum systems

The scaling problem. Many QIST systems – fault-tolerant error-corrected quantum computers in particular – must be scaled up by many orders of magnitude to realize their potential and to achieve "quantum advantage" over classical technologies. The present design of quantum computers is such that every physical qubit must be both controlled and read out by external electronics, not by other qubits. As a result, the number of independent control and readout channels for a quantum computer scales linearly with the number of physical qubits (with some multiplexing techniques enabling constant-factor reductions in the control and readout channel count). This results in a very large number of control and readout channels even for a ~1,000-qubit system, let alone a ~1,000,000-qubit system. Some of the challenges for implementing such a system are described below. Many of these challenges are also relevant for large-scale quantum sensors or networks; the term "qubit" is used as shorthand to mean any smallest-scale quantum element that is part of a large-scale quantum computer, sensor, or network.

The input/output ("I/O") problem. The requirement to connect control and readout signals to their corresponding qubits leads to major I/O challenges when the number of qubits grows large and/or when the spacing between qubits is very small, simply due to physical space and routing considerations. In addition to the increasing number of connections, many quantum devices operate under vacuum and/or at cryogenic temperatures, conditions in which the thermal load from control and readout electronics can pose limits on the ability to scale. Moreover, vacuum and cryogenic operation requirements constrain the materials and methodologies that can be used for connections between the control and readout electronics (which in current devices are typically in air at room temperature) and the quantum processor itself. New technologies are required to increase the channel density and reduce the thermal load associated with the connections between control and readout electronics and the quantum portion of the system.

Increasing integration and reducing C-SWaP. The cost, size, weight, and power dissipation (C-SWaP) of the components that generate, handle, and detect control and readout signals is another major barrier to scaling. Systems to date have been built by assembling a variety of discrete components, a strategy that mitigates risk and affords agility but carries substantial C-SWaP penalties. A shift to increasing integration of components, at the rack/module, circuit board, and chip levels, with an emphasis on C-SWaP reduction, is needed for continued scaling. This will entail development of new technologies, as well as trading flexibility and agility for reduced C-SWaP using existing methods such as application-specific integrated circuits (ASICs). Integration and C-SWaP reduction efforts are relevant for both active and passive components, and for digital, analog, and mixed-signal electronics. Design choices here will impact the I/O problem and vice versa.

Measurement, verification, and validation at scale. As control and readout systems become very large and increasingly integrated, new techniques will be required to test and validate their performance, both during the design phase and when monitoring production or the performance of deployed systems. It will no longer be possible to simply perform testing of all individual components in isolation as is currently done.

Theme #2: Quantum-specific performance characterization and validation

Unique performance requirements for quantum control, readout, and feedback. The rf/microwave and high-speed digital electronics in use in today's quantum information applications were primarily developed and refined for the telecom and classical computing industries. Notable exceptions to this include cryogenic microwave components developed for radio astronomy and satellite communications applications. While many of these technologies have been adapted for use in QIST, the relevant performance requirements and critical specifications for QIST applications can be quite different. Telecom/satcom/digital computing applications can use classical error detection and correction to provide substantial immunity from noise and signal distortion, which is not possible for QIST applications due to the analog nature of their control and readout signals and the high overhead cost for quantum error correction. QIST applications are sensitive to signal phase and amplitude stability, linearity, power dissipation, timing jitter, isolation, and other characteristics at levels that push the specifications of existing off-the-shelf components. To compound the problem, requirements for these specifications can vary widely across different types of quantum processors, making it impossible to define a one-size-fits-all set of performance standards.

Unique demands of the physical environment. Many QIST systems operate under ultra-high vacuum, often at cryogenic temperatures. Components and electronics that must operate in these environments often display changes in performance relative to room temperature operation at atmospheric pressure. These changes are not necessarily detrimental but must be characterized in their target environmental conditions to understand mechanical, electrical, and thermal properties for the design cycle. At present, many QIST researchers have been obliged to carry out extensive component testing on their own to determine suitability of different manufacturer offerings. Many components and brands in common use today are chosen by word-of-mouth recommendation while others are closely guarded secrets. Workshop participants noted the need for well-defined criteria and specifications that encapsulate performance and stability requirements unique to QIST systems. Likewise, there is a need for standard in-vacuum and cryogenic test methodologies and characterization tools that are geared towards non-experts in vacuum and cryogenics.

Standards and traceability for verification and validation (V&V) of control and readout electronics. Existing reference standards and artifacts that might be used for performing calibrations and verification/validation on highly integrated, in-vacuum, and/or cryogenic electronics for quantum applications generally lack traceability to fundamental physical quantities and are prone to systematic errors as a result. New methods to address these shortcomings and provide trusted, traceable calibrations and V&V for control and readout electronics with high integration levels or operating in vacuum or cryogenic environments are needed. Testing throughput requirements for scaled systems mean that these methods need to be compatible with measurement and characterization at the wafer and system scales, not just at the individual device or component level.

Theme 3: Workforce, market, and policy challenges

Small batch/customization. Despite the high level of industry engagement in quantum computing, the field's market share is akin to relatively small R&D efforts from the perspective of established chip or rf/microwave component manufacturers. For this reason, even large quantum computing efforts are often limited either to available COTS components, or much more expensive custom components. This artisanal approach to the construction of control and readout electronics, including cryogenically compatible rf/microwave control and measurement chains and room temperature instrumentation, does not fully benefit from the economies of scale that other modern technologies (e.g., the telecom industry) are able to achieve.

Return on vendor R&D investment. The small market size and high uncertainty in market growth for quantum technologies makes many electronics component vendors hesitant to make significant R&D investments for quantum applications. Likewise, the often narrowly targeted or conflicting specifications for custom components ordered by different QIST end users make it difficult to assess the potential for making standard products (and thus achieving economies of scale) that will satisfy the needs of a variety of QIST customers.

Supply chain. The supply chain for passive and active components is global and, in some cases, relies crucially on a very small number of vendors. For both economic and national security reasons, a robust U.S. supply chain is desirable. However, details of the supply chain, including how many suppliers exist and where they are located, are not clear. In addition, small-volume manufacturing of SiGe, InP and GaAs devices and structures is not readily available. Export regulations may further impede partnership with non-US foundries that do support cryogenic device manufacturing and are more willing to cater to smaller customers.

Workforce. Building large-scale quantum systems requires a wide range of engineering and physics expertise. While the emphasis in much of post-secondary education is focused on understanding quantum mechanics and computing, the specific technical background necessary for building quantum systems includes digital and analog electronics, signal processing, rf/microwave engineering, nanofabrication, and cryogenics. Skills in cryogenics and superconducting and ion trap microfabrication are rarely taught in the US. Instead, much of this expertise has been supplied by researchers with physics backgrounds, often filling roles that would ideally be carried out by trained systems engineers. Expertise also is found among students from other countries who come to the United States for undergraduate or graduate school.

Cryogenic hardware standards. Electronics for cryogenic applications is still a niche market and lacks the widespread adoption of standards and best practices that characterize most other electronics hardware industries (e.g., MIL-SPEC, JEDEC, etc.). The absence of these standards presents a challenge to aggressive investment in cryogenic products and services since standardized metrics for performance in this space do not yet exist.

Import and export restrictions and sanctions. The threat of export controls can hinder research and collaborations and is especially problematic given the global nature of supply chains and technical expertise. The U.S. does not currently have the dominant position in technological capability or products/vendors for QIST-relevant electronics that would be required for export controls to be effective or appropriate. Policy in these areas must be informed by QIS technology roadmaps to form strategic alliances and build a stable, reliable supply chain for US industry. Government should support the development of much stronger domestic resources and capabilities as part of these policy efforts.

Acknowledgements

The following individuals are gratefully acknowledged for their contributions to the organization of the workshop and to writing this report.

Thomas Ohki, Raytheon BBN
José Aumentado, NIST
Daniel Slichter, NIST
Paul Hale, NIST
Ofer Naaman, Google
Joe Bardin, UMass/Google
Guilhem Ribeill, Raytheon BBN
Leonardo Ranzani, Raytheon BBN
Farah Fahim, Fermilab
Clayton Crocker, Keysight
Suren Singh, Keysight
Robin Coxe, Atom Computing
Steve Smith, Cosmic Microwave
Marc Smith, XMA
Del Pierson, XMA
Chris Marki, Marki Microwave
Celia Merzbacher, SRI International (QED-C Executive Director)