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Controlling 1,000 Qubits: How to Scale Quantum Computing for Real-world Impact

April 02 | 2024

The quest to develop practical quantum computers is a unifying goal in our community. This journey, while exciting, presents many challenges that span the entire quantum computing spectrum, from the foundational qubits to the complexities of control hardware and software. Central to this quest is creating a large-scale, functional quantum computer. The crux lies in enhancing qubit quality to achieve lower error rates and longer coherence times.

Recently, a strategic shift has begun to emerge: offloading some challenges to the control layer. This approach marks a significant evolution in tackling the hurdles of quantum computing and paves the way toward realizing its practical potential. In this article, I'll share insights on leveraging control hardware to address these challenges and highlight Quantum Machines' contributions in pioneering this area.

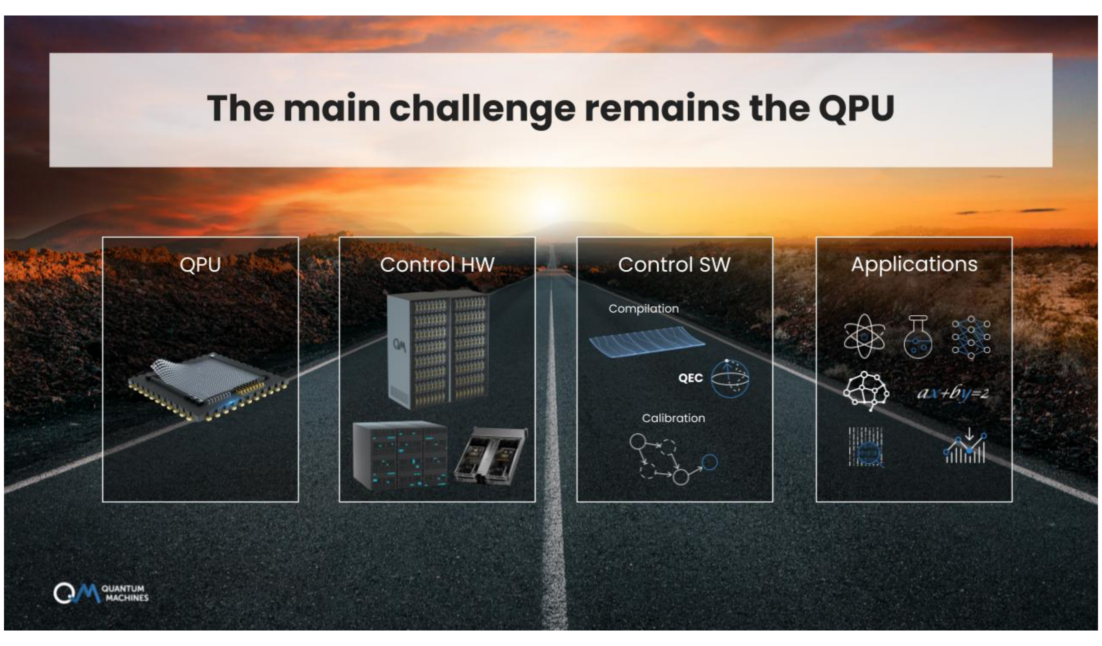
The Layers of Full-Stack Quantum Computing

On the road toward large-scale quantum computing, challenges are present across the entire stack:

- The Quantum Processing Unit (QPU) and the qubits
- The Control Hardware, which includes the classical hardware involved in driving the QPU with analog signals, running quantum programs, and hybrid quantum-classical programs
- The Control Software, which implements the calibrations, compilations, optimizations, and eventually quantum error correction (QEC) on the control hardware and the QPU
- The Application Layers, which will eventually provide real-world use cases for quantum computing

Most of the conversation in our field focuses on the QPUs. After all, this is where the magic happens and where much of the work and progress still needs to be achieved. The rest of the focus is usually given to the application layer – quantum algorithms and their practical application, which is the reason we're in this, to begin with. But lately, some of the focus has been shifting to the stack's control layers. These layers are positioned right in the middle and hold the potential to help optimize performance and increase the productivity of research and development.

There is still a long way to go before quantum computers can efficiently solve real-world problems of practical interest. So, how do we make faster progress toward this common goal?



Control Hardware's Role in Advancing Quantum Computing

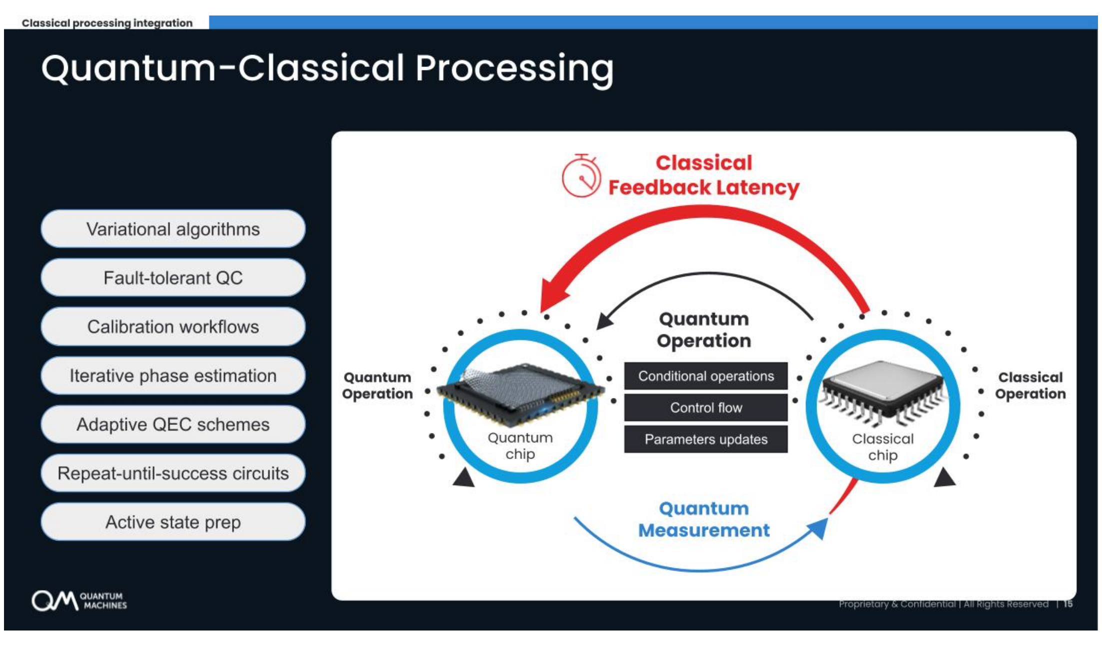
While there are hurdles across the entire stack, the quantum processing unit (QPU) still presents the biggest one. The main issue is creating better qubits while gradually getting lower error rates and higher coherence times. Recently, a new strategy has emerged to overcome the current challenges of the QPU layer. This strategy involves shifting some of the weight from the QPU to the more mature classical control layer, both in terms of hardware and software. This approach can compensate for current QPU limitations and even go beyond mere compensation, offering a practical path forward as we work towards perfecting qubits. **In other words – as long as our qubits aren't perfect, our quantum control must be.**

I'll now focus on the control hardware and its vital role in optimizing QPUs and qubit performance. Let's begin by defining the criteria for effective quantum control hardware. To be truly useful, control hardware requires four critical aspects: scaling up, analog specifications, quantum-classical integration, and programming flexibility.

The Four Pillars of Quantum Control Hardware

Scaling Up: It's a misconception that scaling in quantum computing is straightforward. Unlike classical computers, quantum control systems must scale linearly with the quantum processor's size. Since we don't yet have perfect qubits, we parallelize operations to maximize their number within the qubits' coherence time. Scaling to thousands of qubits is complex, involving not just the number of control channels but also the channel density, synchronization between them, and cost-effectiveness: price per qubit, price per channel, or the control channel per qubit.

Analog Specifications: Optimizing control system performance is crucial for pushing the limits of fidelity in quantum computing. To have a wider variety of gates, we add requirements to the controller. This means carefully managing analog specifications to ensure high-quality gate performance on a large scale. Theoretically, we can do any quantum processing with a simple set of gates. In practice, however, we use a much richer gate set than the universal one because we seek to optimize the circuits. Consequently, the overhead on the control system increases, which becomes an even more significant challenge as we scale. Think of having 1000s of channels synchronized in terms of phase without drifting in your signals.



Quantum-Classical Integration: A core area for us here at Quantum Machines, quantum-classical integration involves a cycle of quantum operations, followed by measurements, then classical processing within the classical device, classical operations, and finally, generating new quantum operations based on this classical feedback. This feedback loop is essential in quantum computing for various applications, including active state preparation, repeat-until-success circuits, adaptive quantum error correction schemes, calibration, workflows, variation algorithms, and more.

We have defined three new categories for efficient quantum-classical integration:

- Quantum Real-Time (QRT): The feedback latency must be considerably lower than the time the qubit takes to change coherence times.
- System Real-Time (SRT): Feedback latency must be much smaller than the system drift time.
- Near Quantum Real-Time (NQRT): Feedback latency must be much smaller than the total quantum computation time so it does not bottleneck the total runtime of our application.

Programming Flexibility: Programming flexibility is key to developing better quantum processors. It enables quick iterations and modifications in quantum algorithms and error correction techniques. Currently, we still too often program the hardware for operations like real-time performance. It's resource-heavy and takes quite a long time to set up and then even more to tweak when adjusting for the algorithm. Efficient control hardware must allow quick programming and iterations via the software without altering the hardware.

Addressing Quantum Control Hardware Challenges

At Quantum Machines, we've made significant strides in addressing the challenge of the control hardware. By integrating classical compute engines directly into the heart of the quantum control system, our OPX quantum controller™ significantly enhances efficiency and functionality. This integration facilitates real-time signal generation, enabling an exceptionally tight and seamless quantum-classical loop. This not only enhances the speed and precision of quantum computations but also significantly reduces the latency typically associated with such complex processes.

Expanding upon the foundations laid by the OPX, we developed OPX1000. This system represents a massive leap in quantum control technology, featuring a massively scaled-up architecture with high-density control channels. OPX1000 is engineered to be data-center-ready, embodying a robust design equipped to handle the demands of large-scale quantum computing operations. It includes state-of-the-art analog specifications, ensuring unparalleled fidelity and precision in quantum gate operations. With its advanced capabilities, OPX1000 can manage thousands of channels, making it an ideal solution for the most demanding quantum computing applications.

Industry Collaboration with NVIDIA

In order to continue to push the frontiers of quantum computing, we embarked on an ambitious collaboration with Nvidia through the DGX Quantum project. This partnership is set to redefine the standards of quantum-classical integration by merging our advanced control systems with Nvidia's high-performance compute engines, particularly the cutting-edge Grace Hopper platform. This integration aims to achieve ultra-low latency in quantum-classical processing, a critical factor in enhancing the efficiency and speed of quantum computations. The synergy between Quantum Machines' control systems and Nvidia's computational power creates an unparalleled platform for quantum computing, paving the way for more complex and sophisticated quantum algorithms.

Future-proof Quantum Control

These strategic advancements at Quantum Machines mark a significant transition from research and development into implementing large-scale, production-ready quantum control systems. By continuously innovating and pushing the boundaries of quantum computing technology, we are not just keeping pace with the quantum computing world's evolving needs but actively shaping its future.

Our commitment to excellence and innovation ensures that we remain at the forefront of this exciting and rapidly advancing field, contributing to the acceleration of quantum computing's potential to solve some of the world's most complex problems.

Discover More

Contact us or *request a demo* to learn more about Quantum Machines, *OPX+* and its scaled-up version *OPX1000* to better understand how these unique processor-based controllers can accelerate your research.

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