Computing Systems for Superconducting Qubits: Challenges and Opportunities

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Abstract

Superconducting qubits have emerged as leading candidates for realizing quantum computers, which are particularly useful for solving computational problems that are beyond the capabilities of classical supercomputers. The performance of such systems critically depends on the precision and reliability of their control infrastructure. In this paper, we present an overview of state-of-the-art quantum control systems, including both closed- and open-source solutions, and discuss their respective advantages and limitations. While we review both categories, we focus more extensively on open-source control platforms and explore how their flexibility and programmability can support the research community and drive progress in the field. Lastly, we outline several promising research directions in quantum computing infrastructure, including scalable control, high-precision readout, and leakage suppression. We believe that these areas should be prioritized by the community, as they are critical to realizing fault-tolerant quantum computation.

CCS Concepts

• **Computer systems organization → Quantum computing**.

Keywords

quantum control systems, quantum computing, superconducting qubits, computing systems, machine learning

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1 Introduction

Quantum computing represents a transformative shift in computational power, offering the potential to solve problems that are currently intractable for classical computers such as prime factorization, quantum simulation, cryptography. At its core, quantum computing leverages the principles of quantum mechanics, such as superposition, entanglement, and quantum interference, to perform calculations exponentially faster than traditional computing in specific problem domains. Several physical platforms have been explored for quantum computation implementations, including trapped ions, photonics systems, spin-based qubits, neutral atoms, topological and superconducting circuits [6].

Among these, superconducting circuits have emerged as the leading platform for scalable quantum computing. Their advantages include fast gate times, compatibility with existing fabrication technologies, and ease of integration with cryogenic control electronics [6]. As a result, major industry players such as Google[1], IBM[7], and government laboratories like Berkeley [26] and Fermilab [22] have adopted superconducting qubits as the foundation of their quantum processors, demonstrating significant progress towards large-scale, fault-tolerant quantum computers.

Superconducting qubits are built from superconducting circuits operating at millikelvin temperatures, where electrical resistance vanishes, allowing for high-speed, low-power operation. These qubits are controlled using microwave pulses, usually in the gigahertz range [22, 26], which manipulate the quantum state of the qubit to perform logic gates and measurements. The infrastructure responsible for generating and analyzing these pulses is known as the quantum control and readout system [8, 22, 26]. Acting as the interface between classical and quantum domains, these systems are essential for initializing, controlling, and reading out quantum states. Over the past decade, advancements in such systems have significantly improved qubit performance and coherence times.

Despite this progress, many challenges remain in realizing practical large-scale quantum computing. Chief among them is the precise control and high-fidelity readout of an increasing number of qubits. As the system scales, mitigating noise, decoherence, and control cross-talk becomes increasingly difficult. Achieving quantum supremacy and eventually fault-tolerance requires control systems capable of generating highly specific, noise-resilient microwave pulses [8].

Moving forward, significant progress must be made across system-level components: cryogenic electronics, control scalability, low-noise operations, and real-time error correction. As the number of qubits increases, the complexity of the control architecture grows, prompting leading companies and national labs to invest in robust and scalable control platforms [7, 22, 26].

In this paper, we focus specifically on open-sourced RFSoC-based control platforms and highlight key components such as microwave pulse generation, readout, and quantum state discrimination. We compare commercial and open-source quantum control platforms, emphasizing trade-offs in flexibility, scalability, and accessibility. We then highlight recent studies using open-source platforms in areas like compressed waveform generation for scaling, ML-based state discrimination, and mid-circuit measurements. Finally, we outline open challenges for computer scientists—including topics such as readout precision, real-time feedback, HPC/control-system communication, pulse optimization, and leakage suppression—as we advance toward building large-scale quantum computers. While our survey parallels those in the physics domain, it focuses specifically on the computing aspects of quantum control; readers seeking discussions on qubit physics, fabrication, or hardware-level details may consult existing reviews [6, 8].

2 Overview of Quantum Control Systems

In this section, we provide an overview of current superconducting qubit systems, emphasizing their architectural and systems-level properties from a computer science perspective.

2.1 Background

The superconducting quantum system primarily consists of three main components: (1) the qubit chip, (2) cryogenic, and (3) room-temperature electronics. The quantum chip is located inside the dilution fridge and must be kept at ultra-low temperatures, typically around 10mK, to preserve its quantum properties. The control system, usually located outside the cryostat (Figure 1), uses microwave pulses, generally in the 4–8 GHz range, to control and manipulate qubits [6, 14]. These control pulses are often generated in parameterized forms, and their shape and quality significantly influence qubit state fidelity and coherence properties.

As illustrated in Figure 1, the blue enclosure represents a dilution refrigerator capable of reaching ultra-low base temperatures around 10 mK. Housed inside the refrigerator are the quantum chip and associated cryogenic wiring. The remainder of the diagram shows the schematic of the room-temperature (300 K) control electronics. Each qubit on the chip is fully controllable via a capacitively coupled microwave control line and an inductively coupled bias line. The microwave control line enables coherent manipulation of qubit states—such as transitions between $|0\rangle$ and $|1\rangle$ - and is driven by a microwave arbitrary waveform generator (AWG), which consists of FPGAs, DACs, and IQ mixers - in case the DACs' speed is not high enough [6]. The coupled bias line is used to tune the qubit's operating frequency, with signals from both the fast and slow control paths combined through a bias tee. Waveforms directed to the readout line induce a dispersive interaction between the qubit and a harmonic resonator, enabling qubit measurement and readout.

Fast and reliable qubit state readout is key to quantum computing. Readout refers to the measurement process by which the quantum

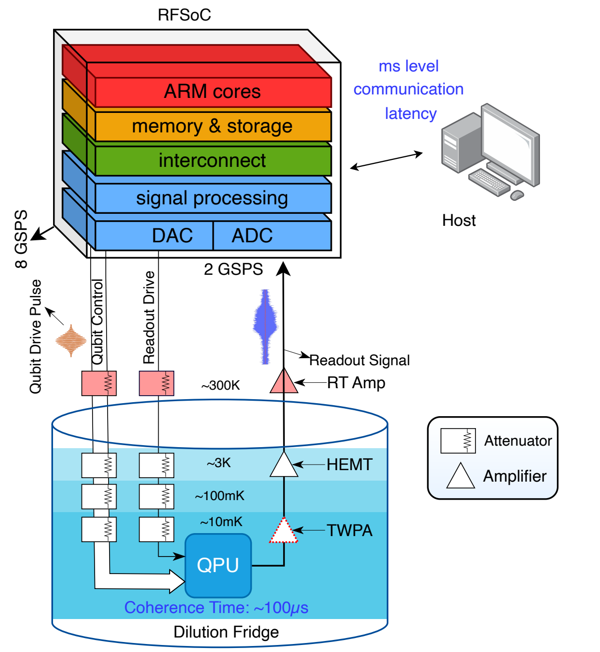

Figure 1: Schematic of a typical RFSoC-based superconducting transmon qubit control and readout system.

state of a qubit is converted into a classical bit value. While various readout methods exist, dispersive readout is typically applied in recent years. The coherence time of the qubit is increasingly limited by the Purcell effect, where energy spontaneously decays into a nearby oscillator mode. To mitigate this effect, so-called Purcel filters, acting as band-pass filters, are used to make the interactions between the resonator and an output line strong while protecting the qubit from energy decay. This readout method requires relatively low photon numbers which must be amplified for fast and high-fidelity single-shot readout. Current state-of-the-art quantum control systems utilize frequency-multiplexed readout circuits to reduce the hardware overhead by coupling many readout resonators to the same amplifier chain.

The development of quantum control systems has progressed over the year, initially focused on simple quantum systems and advancing to the current sophisticated systems required for Noisy Intermediate-Scale Quantum (NISQ) area. State-of-the-art quantum processors from IBM, which has 1121 qubits, need many RF cables per qubit [7, 16]. However, as the number of qubits increases, the control infrastructure becomes more sophisticated, requiring complex interconnect for multiple control boards, posing a significant challenge for scalability. While both commercial and open-source quantum bit control systems are currently available on the market, they do have certain pros and cons. With that being said, challenges still remain in the precision and scalability of practical quantum computing.

2.2 Commercial Quantum Control Systems

Several companies like Zurich Instruments, Keysight, and Quantum Machines offer advanced, high-performance commercial quantum control systems featuring FPGA-enabled pulse synthesis. These systems follow a conventional approach in which the FPGA-controlled digital-to-analog converters (DACs) synthesize the intermediate frequency (IF) envelopes. These envelopes are then up-converted using in-phase and quadrature (IQ) mixing modules with a local oscillator. A deeper comparison of commercial control systems is not possible since their technical reports and specifications are confidential. Therefore, we primarily focus on open-source quantum control systems and recent research in this paper. A comparison of current commercial qubit control systems is summarized in Table 1

2.3 Open-Source Quantum Control Systems

In parallel with commercial solutions, many researchers, including our team, have devoted significant effort to developing robust and flexible open-source quantum control systems to support experimental research, accelerate innovation, and enable reproducibility across the quantum computing community [25]. These systems allow researchers to construct and customize experimental control architectures, promoting innovation and reproducibility within the quantum community.

Current open-source quantum control platforms are primarily implemented on AMD FPGA RFSoC devices due to their monolithic integration of high-speed analog-to-digital converters (ADCs), digital-to-analog converters (DACs), ARM cores, and field-programmable gate array (FPGA) fabric. The tight coupling between RF front-ends and programmable logic facilitates ultra-low-latency control loops, high-bandwidth waveform generation, and real-time processing, all essential for scalable quantum error correction and feedback protocols. Due to the modality, open-source systems offer a significantly lower per-channel cost than existing commercial solutions, along with complete access to all layers of the control stack. Most open-source quantum controllers are developed using Verilog for hardware architecture design, and Python for software development and programming. Among the most prominent open-source platforms are QubiC, QICK, SQ-CARS, and Presto, which illustrate the state-of-the-art in community-developed control stacks.

QubiC 2.0 [26], a flexible and advanced full-stack quantum bit control system, developed by Berkeley Lab, is an open-source control system designed for quantum information research. It is highly flexible, supporting a wide range of quantum processors and experimental setups. It integrates a 16-channel, 14-bit DAC operating at 8 GSPS and a 2 channel, 14-bit ADC at 2 GSPS, enabling high fidelity data acquisition. The pulse generation in QubiC is parameterized by amplitude, phase, and frequency, allowing for real-time updates between pulses. Furthermore, QubiC also enables real-time mid-circuit measurements and conditional operations based on measurement outcomes. QubiC employs a two-stage software toolchain consisting of a compiler and an assembler. The compiler translates high-level quantum programs, including control flow constructs, into calibrated pulse-level instructions for each qubit. The assembler then integrates these with hardware configuration data to generate executable binary commands for the distributed FPGA processors. QubiC achieves 0.9980 ± 0.0001 fidelity for single-qubit process and 0.948 ± 0.004 for the two-qubit process. This capability is crucial for implementing advanced quantum algorithms, including quantum error correction and measurement-based quantum computing.

QICK [22], developed by Fermi Lab in 2022, integrates control and readout for up to 8 qubits on the RFSoC technology. It supports direct control pulse synthesis with carrier frequencies of up to 6 GHz. The gateware leverages built-in digital-to-analog (DACs) converters in the RFSoC board for arbitrary waveform generation for RF pulses and enables fast, precise measurements via the analog-to-digital converters (ADCs). Furthermore, it also has a custom timed-processor (tProcessor) that users can program a sequences of precisely timed pulses and control loops through a low-level programming language. The readout fidelity measured by QICK with a bi-modal Gaussian function for single-shot measurements is 94.7%, which is on par with the AWG-based system and the OPX from Quantum Machines. Additionally, The average gate fidelity is $F_{\text{avg}} = 99.93\% \pm 0.01\%$, and the coherence-limited gate fidelity is around $F_{\text{lim}} = 99.96\%$. For the gen 3 version evaluated on the ZCU216 hardware, QICK firmware was developed for direct, mixer-free pulse generation for qubit drives and multiplexed readout up to 10 GHz [3].

SQ-CARS [20] also uses the RFSoC technology, capable of supporting up to four qubits. It enables the direct synthesis of arbitrary vector microwave pulses in the 4–9 GHz range by leveraging the second Nyquist zone. The design utilizes multi-tile synchronization (MTS) in conjunction with onboard numerically controlled oscillators (NCOs) to minimize inter-channel delays caused by FIFO buffering and NCO processing. An external 10 MHz reference clock is used to drive the onboard phase-locked loop (PLL) for clock synchronization. For direct digital microwave pulse synthesis, a mixed-mode technique is employed to enhance frequency generation.

3 Recent Research Benefiting from Open-Source Quantum Control

The growing availability of open-source quantum control systems has provided researchers with highly customizable and cost-effective tools for advancing research in quantum computing. By enabling researchers to tailor and experiment with control systems, many novel architectures and methods have been proposed and evaluated, paving the way to the realization of practical quantum computing.

Maurya *et al.* [9] address the significant challenge of achieving low-latency, high-fidelity qubit readout in superconducting quantum processors, where readout error rates typically range from 1% to 10% due to effects such as crosstalk, spontaneous qubit transitions, and measurement-induced excitations. While prior approaches have employed deep neural networks for single-shot qubit state classification to improve accuracy, their large model sizes pose significant challenges for deployment on field-programmable gate arrays (FPGAs). To overcome this limitation, they propose *Herqles*, a hardware-efficient framework that combines a hierarchy of matched filters with a lightweight and scalable neural network architecture. Implemented on FPGA for real-time processing, Herqles achieves a 16.4% relative improvement in readout accuracy over state-of-the-art baselines. Additionally, it maintains robustness under shorter readout durations without requiring additional training overhead, making it a practical and scalable solution for improving quantum measurement fidelity in near-term quantum computing systems.

System	OPX1000 [19]	SHFQC+[27]	Keysight Quantum Engineering Toolkit[18]	QCM [17]	Presto [23]
Frequency	100 MHz – 10.5 GHz (DDS-based, no mixers)	DC – 8.5 GHz (no mixer calibration)	9 kHz – 12 GHz	2 GHz – 18.5 GHz	10 MHz – 10 GHz
DAC	10 × 16-bit, 1 GSPS	8 × 16-bit (2–4 GSPS)	4 × 14-bit (500 MSPS, 1 GSPS)	2 x 16-bit (1 GSPS)	14-bit DAC (up to 10 GS/s)
ADC	10 × 12-bit, 1 GSPS	14-bit, 4 GSPS	4 to 8 channels × 14-bit (100 MSPS)	Not clearly stated	14-bit ADC (up to 5 GSPS)
Key Features	16 cores Hybrid Processing Unit, real-time pulse generation and modulation	multi-state discrimination, signal processing chain with matched filters, frequency-multiplexed qubit readout	Modular architecture with scalable PXIe chassis, $< 100ns$ pulse output latency	synchronization $<< 1ns$ with SYNQ, LINQ for data sharing across devices in $< 364ns$	Massively parallel FFT, direct signal synthesis, programmable NCOs, matched filtering
Scalability	1000 qubits at beyond with QSync synchronization technology	6 qubits / single system, 336 fixed-frequency qubits with QHub Quantum System Hub	modular PXIe chassis to integrate modular hardware, up to hundreds of qubits	Up to 1000 qubits with the Communication Module	Large scale QPU control with Metronomo synchronizations
Latency	Active reset $< 160ns$	active reset $< 350ns$	feedback loops $< 210ns$	Fast reset $< 400ns$	$< 200ns$ feedback

Table 1: Comparison of some commercial quantum control systems.

Neel *et al.* [25] introduce QubiCML, a novel FPGA-based system designed for real-time qubit state discrimination, deployed on top of the QubiC [26], enabling mid-circuit measurements in superconducting quantum processors. Unlike conventional discrimination techniques that rely on offline analysis and suffer from slow host communication, QubiCML offers an in-situ solution for low-latency, high-accuracy feedback, which is critical for implementing advanced error correction algorithms in noisy intermediate-scale quantum (NISQ) devices. The system uses a multi-layer neural network deployed on an Xilinx ZCU216 RFSoC platform and achieves 98.5% state discrimination accuracy with readout times as short as 500 ns. The QubiCML platform's ability to perform real-time qubit state measurement and feedback opens up new possibilities for quantum algorithm development and optimization, marking a significant advancement in quantum control systems. This work represents the first implementation of machine learning-powered state discrimination for mid-circuit measurement on an RFSoC platform, highlighting its potential as a tool for real-time state measurement in quantum computing.

In another contribution, Maurya *et al.* [10] propose COMPAQT, a compressed waveform memory architecture, a compressed waveform memory architecture that reduces bandwidth and memory overhead, thus increasing the number of qubits that can be controlled by a single RFSoC-based setup. In typical quantum control systems, qubit gates are implemented by streaming microwave waveforms from memory to DACs, which can require tens of Gbps per qubit. This requirement scales linearly with the number of concurrently controlled qubits. COMPAQT addresses this challenge by compressing waveform libraries at compile time, storing the compressed waveforms in memory, and decompressing them in real-time for transmission to DACs. When validated on top of QICK[22], COMPAQT enables control of up to 191 qubits concurrently - far surpassing the theoretical 36-qubit support in the original QICK implementation.

In all of these projects, open-source quantum control systems such QICK, and QubiC2.0 have served as the foundational platforms for advancing cutting-edge research in quantum control systems. Their flexibility and customizability have enabled the development of innovative techniques in quantum computing. These open platforms not only promote collaboration and transparency in the quantum research community but also open up diverse research avenues for exploration, particularly in areas such as real-time feedback, error correction, scalability, and multi-qubit operations.

4 Potential Research Directions

Research revolving around quantum control systems is advancing rapidly, presenting numerous opportunities for computer scientists to contribute novel solutions that can significantly improve the performance and scalability of quantum processors. This section outlines several promising research directions poised to accelerate progress in quantum control, particularly through the integration of machine learning (ML), artificial intelligence (AI), system-level software, and emerging hardware architectures.

4.1 Machine Learning for Readout

As quantum computing systems continue to scale, accurately classifying quantum states becomes increasingly challenging. Traditional state classification methods, based on direct or projective measurements, may not be efficient or fast enough for large-scale quantum systems. A promising direction involves leveraging machine learning (ML) algorithms for real-time multi-level qubit state readout [13]. Machine learning models, such as neural networks, can be trained to classify quantum states from noisy, high-dimensional time-domain data generated by superconducting qubits and other quantum hardware [9, 13, 25].

Research in this area may focus on developing ML models capable of accurately measuring quantum states under noise and partial observability. These models can improve the fidelity of qubit measurements, even in the presence of imperfect control signals. Moreover, physics-informed machine learning offers a compelling approach to incorporate prior physical knowledge into learning models, further enhancing robustness and accuracy [15]. A particularly exciting direction involves hybrid ML techniques that combine classical data processing with quantum measurements to enable real-time state estimation and error correction.

Given that qubit coherence times typically last only a few microseconds, ML-based state classifiers must be both fast and lightweight, ensuring that inference completes before the quantum state decoherence. Achieving this efficiency requires optimization at both the algorithmic level [5] and the hardware level. Hardware acceleration, through custom design or high-level synthesis, has emerged as a key strategy for deploying these ML models in practice [2, 9, 13, 25].

4.2 Mid-Circuit Measurements for Quantum Circuits

Mid-circuit measurements, also known as in-situ measurements, are becoming increasingly crucial for enhancing the efficiency of quantum computations. They reduce the need for qubit resets and enable circuits to adapt dynamically during execution. Recent developments, such as QubiCML [25], demonstrate how machine learning (ML) algorithms can facilitate real-time quantum state discrimination, significantly advancing this area.

A natural extension of this work lies in improving the accuracy and reliability of mid-circuit measurements using ML-based prediction of measurement outcomes, thereby offering more precise insight into qubit states during computation. Future research could focus on minimizing the disruptive impact of measurements, especially in multi-qubit operations, by incorporating real-time feedback mechanisms for on-the-fly state correction. Further, optimizing measurement timing and extending coherence during measurement events could enhance overall system performance. Real-time mid-circuit measurements at scale would be a key enabler for advanced algorithms such as quantum error correction and quantum optimization, paving the way for more powerful quantum processors.

4.3 Ultra-Low Latency High-Performance Computing / AI Accelerators Data Transfer

Quantum control systems often involve transferring large volumes of quantum measurement data (ADC signals) to high-performance computing resources for post-processing. In particular, real-time feedback systems, such as error correction or state discrimination models, require ultra-low latency data transfer between quantum processors and classical HPC resources. While software-based post-processing, including neural networks running on CPUs or GPUs, offers rapid prototyping and experimentation compared to dedicated hardware implementations, the primary bottleneck remains the data transfer latency between the control system and host computer. This latency typically spans microseconds (Figure 1), which exceeds the coherence time of current superconducting qubits.

A critical research direction is therefore optimizing this data transfer pipeline to ensure measurement results can be processed in real-time with latency below qubit coherence times (approximately 100 μs). Potential solutions include designing specialized communication protocols and custom hardware interfaces that enable ultra-low latency data transfer from ADCs in quantum control systems to HPC or AI accelerator platforms. Achieving such fast transfer is essential for closing the feedback loop quickly and reducing the delay between measurement and control signals. Once ultra-low latency transfer is realized, software-based algorithm development and testing will accelerate, potentially leading to near-perfect readout fidelity and more effective quantum control.

4.4 Scaling

Scaling up the number of qubits is critical for achieving quantum advantage. This section explores potential research directions to support scalable quantum control. Broadly, two primary approaches can be pursued: (1) interconnecting multiple control systems to build a larger infrastructure, and (2) increasing the number of qubits that can be managed by a single control board.

As the number of physical qubits grows, it can quickly exceed the capacity of a single FPGA-based control and readout system. Consequently, multi-board synchronization becomes essential. Several techniques have been developed to address this challenge. For example, Xu et al. [26] achieved synchronization using a precision clock protocol that distributes a shared reference clock across multiple boards. Future research could focus on developing scalable interconnects and communication protocols capable of synchronizing quantum controllers not just across identical systems, but also across heterogeneous platforms [12].

Each quantum gate is implemented via microwave pulses in the gigahertz range, and each qubit requires unique control and readout waveforms. As more qubits are controlled by a single board, the demand for waveform memory increases significantly. To manage this complexity, two complementary research directions emerge: optimizing FPGA hardware architectures for efficient pulse generation [10], and developing methods to optimize the control pulses themselves [21]. Addressing these challenges is essential for realizing scalable, high-fidelity quantum computers.

4.5 Leakage Suppression

Noise remains one of the greatest challenges in quantum systems, especially in large-scale quantum computing. As qubits become more numerous, maintaining coherence and reducing noise becomes increasingly difficult. Quantum Error Correction (QEC) helps protect and stabilize quantum computers by encoding quantum information in a way that allows errors to be detected and corrected.

Ideally, qubits in a quantum system are expected to remain in their computational basis states, denoted by $|0\rangle$ and $|1\rangle$. However, qubits can transition to a non-computational state known as the leaked state 'L' due to the narrow energy gap between computational states and higher excited levels. Leakage transitions, induced by thermal fluctuations, quantum gate operations, or measurement processes, can drive qubits out of their computational basis. A recent study by Google [11] shows that leakage errors degrade the performance of quantum error correction codes (QEC) on real hardware. Such errors occur in quantum computers when a qubit leaves its computational basis and jumps to higher energy states. Leakage will continue spreading if not removed, affecting more and more qubits over time, making QEC codes more vulnerable [24]. Research on leakage suppression will make quantum error correction more reliable and accelerate research towards fault-tolerant quantum computing.

4.6 Tooling

Successful quantum computing algorithm deployments rely on both quantum hardware and middleware software designed for control systems across various quantum platform technologies. The primary purpose of middleware is to offer standardized software that abstracts complex software interfaces, making it easier for high-level applications to interact with underlying hardware. Currently, one of the major challenges in the middleware is the need for standardized code procedures for quantum control algorithms, calibration, and characterization. The software should be designed for reuse across similar experiments in multiple research laboratories focused on quantum hardware design and fabrication [4].

5 Conclusions

Quantum control systems are crucial for unlocking the potential of quantum computers. Existing solutions have enabled current experimental progress but suffer from issues of scalability, portability, and ease of use. We argue that future research must explore system software innovations, machine learning, and hardware-software co-design to overcome these limitations. These challenges open exciting opportunities for the computer systems community to contribute to the quantum computing revolution.

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