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Synergizing Error Suppression, Mitigation and Correction for Fault-Tolerant Quantum Computing

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***Abstract*—Quantum computing has showcased potentials to address classically unsolvable problems and attracted research investigation all around the world. However, quantum devices are inherently noisy and create hurdles from true quantum supremacy. Despite researchers have strived to demonstrate quantum advantages at small scales in the noisy intermediate-scale quantum (NISQ) era, we are now at the turning point to craft fault tolerant quantum computers (FTQC) for large scale quantum computing. In this paper, we review the current status of available error control techniques, discuss the missing pieces of each technique for their practical adaptation, and envision the necessity to synergize them across vast design stacks, to enable fault tolerance in quantum computing.**

***Index Terms*—quantum computing, fault tolerance.**

I. INTRODUCTION

Leveraging qubit superposition and entanglement, quantum computing has the promise to offer exponential speedup in computation and revolutionize science, cryptography artificial intelligence, finance and beyond. Qubits are inherently noisy, which do not exhibit the expected quantum supremacy. To take advantage of existing noisy quantum computers, researchers focus on NISQ algorithms [1] and seek to distill meaningful information from noises. At tens of qubits scale, quantum advantages have been demonstrated in the real world. To enable such advantages, quantum error suppression (QES) and quantum error mitigation (QEM) are essential techniques. However, as further scaling up the quantum computers, i.e., the number of qubits goes up, quantum error correction (QEC) technique will be inevitable to bring about fault tolerance to quantum computing. Both the industry and academia researchers have anticipated FTQC for large-scale (e.g., millions of) qubits in forthcoming decades. Since these different error control techniques are designed for different purposes, their relevant theory, software and hardware supports are distinct. In pursuit of FTQC, we expect these distinguished techniques will coexist with each other. Importantly, they are also at different levels of maturity. Given the current infancy of quantum error correction, there are very limited supports across the system design stacks, especially on software and hardware. We argue that (1) existing stacks for QES and QEM need to be further extended to improve themselves and facilitate the development of new stacks for QEC, and (2) QES, QEM and QEC will coexist and synergize with each other to shorten our journey towards FTQC.

II. STATE-OF-THE-ART ERROR CONTROL TECHNIQUES

A. Quantum Error Suppression And Mitigation

QES addresses errors at the hardware source. It leverages prior knowledge of hardware-biased errors to build noise-resilient quantum operations. This method incurs minimal resource overhead, which can often be ignored. In contrast, QEM operates at the software level, i.e., applied in classical domain. Its primary goal is to derive noise-free expectation values for many quantum algorithms. However, QEM typically oversamples the computation, making it challenging to scale. For example, common QEM methods such as zero noise extrapolation [2], Clifford data regression [3], and probabilistic error cancellation [4] incur linear, polynomial, and exponential sampling overheads. Despite the overhead, QEM has helped demonstrated first instance of quantum utility [5]. Another way to reduce errors is to optimize quantum circuits through techniques such as noise-aware circuit compilation and gate optimization. The synergy between circuit optimization and QES has been shown to improve the fidelity of quantum algorithms by up to 1000 times [6].

B. Quantum Error Correction

Rooted in information theory, QEC encodes multiple physical qubits into logical qubits according to error correction code. The errors can be corrected via parity checks between data and syndrome qubits. Through the measurement of syndrome qubits, the decoder (classical computers) will identify the location of possible errors, which are later corrected. With the error rate in physical qubits below a certain threshold, logical qubits can exhibit arbitrarily low error rate, as one increases the code size. Example QEC codes include stabilizer code, CSS code, surface code, LDPC code, and many more. Recently, QEC has significant advancements in theory, software and hardware. The amount of qubits in QEC code has gone beyond tens of thousands [7]. The numerical simulators are under active development to support thousands of qubits [8]. Small-scale (a few qubits) QEC experiments have been demonstrated on real-world quantum computers [9].

III. OUR VISION

A. Quantum Error Suppression And Mitigation

Both QES and QEM have demonstrated significant improvements in the fidelity of hardware results. QES, which relies on

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the interaction with the hardware, faces a challenge of building accurate noise models for quantum hardware. Specifically, the quantum hardware is an open quantum system, with non-negligible interaction with the environment involving non-unitary dynamics. This interaction introduces complexity to noise modeling, and the fact that different hardware platforms have distinct error sources makes it difficult to accurately identify and model them. Even after identifying the error sources, engineering robust QES techniques to eliminate these errors remains a significant hurdle. On the other hand, QEM methods, which operate at the software level, are effective at removing certain types of errors but often suffer from substantial overhead. The only unbiased QEM method, probabilistic error cancellation, has exponential overhead. Therefore, developing resource-efficient and less biased QEM methods is crucial. Additionally, analyzing the resource requirements and performance of combining different QEM techniques could lead to more efficient strategies for error reduction. Quantum circuits implementing quantum algorithms are usually highly structured, and different algorithms may be affected differently by specific types of noises. Integrating hardware-software co-design approaches by combining QES and QEM techniques could enhance the performance of quantum algorithms in the NISQ era, ultimately accelerating the development of practical quantum applications.

B. *Quantum Error Correction*

QEC actually constructs an explicit loop between the classical and quantum components, which puts QEC on the critical path in FTQC systems. Important constraints have to be considered to ensure the correction can be completed before decoherence, including numerical accuracy, hardware area, power and latency, and beyond. Depending on the qubit technology, the above factors could vary largely. To pave the way toward future FTQC given the undetermined winner of qubit technologies, QEC research shall take a hybrid approach. We need to support the general numerical simulation for different QEC codes to identify the most promising code from a theory perspective. The simulation framework needs to be distributed and parallelized, so that QEC codes at million qubits scale can simulated. The framework also needs to consider complicated, technology-specific error models. Existing error models for numerical simulations are too simple to capture the sophisticated noises [8]. Moreover, we need to innovate decoding algorithms to unleash the true power of good QEC codes. Decoding algorithms have drastic variations in computational cost, hardware complexity and exploitable parallelism. Ill-suited decoding algorithms fail to successfully complete QEC with all the applied constraints. We also need to orchestrate hardware-centric QEC system, where software interaction is minimized, since software-based QEC have been proven to violate the system constraints [10]. To achieve the goal, we need to design architecture abstractions and customize technology-specific decoder architectures, that optimally balance all the constraints above. The decoder could be single-stage global, double-stage local-global, or even distributed architecture, depending on the qubit technology and the scale of the quantum computer.

C. *Synergy Among Suppression, Mitigation And Correction*

Though for different purposes, QES, QEM and QEC are all mandatory for realistic FTQC. The success of QES and QEM permit them to synergize with QEC and push forward the boundary of FTQC. Since QES can reduce errors directly at the hardware level, it naturally enhances the efficiency of QEC. By addressing certain errors through QES, we can simplify the remaining errors that need to be handled by QEC, potentially reducing the code distance and resource overhead required for QEC. FTQC requires substantial overhead, particularly for non-Clifford gates, which typically necessitate resource-intensive magic state distillation. One possible way to reduce this overhead is to apply QEC to Clifford gates while using QEM for non-Clifford gates. This approach enables partial error correction, potentially introducing practical quantum applications and bridging the gap between NISQ and FTQC, enabling seamless transition. One more important aspect of FTQC is the software design stack. Current software stacks for addressing errors in the NISQ era primarily focus on two-qubit gate errors. However, in the realm of FTQC the most challenging errors arise from single-qubit non-Clifford gates. New tools have to be developed for resource estimation in fault-tolerant circuits and for developing architectures that integrate QES and QEM with various QEC codes for FTQC in a resource-efficient manner. That said, the success of existing circuit simulation techniques opens up candidate optimizations for future large-scale fault-tolerant circuit simulation.

IV. CONCLUSION

In this paper, we review the state-of-the-art error control techniques in quantum computing, discuss the missing pieces of each and envision their synergy towards fault-tolerant quantum computing, shedding lights on future research directions.

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