Quantum-Hardware Focused Application Performance Benchmarks
Final Technical Report

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Overview

Quantum-Hardware Focused Application Performance Benchmarks was a collaborative project between Duke University (PI: Kenneth Brown) and Virginia Tech (PI: Sophia Economou). The project worked closely with the Methods and Interfaces for Quantum Acceleration of Scientific Applications (MIQASA) project at Oak Ridge National Laboratory (PI: Rafael Pooser). The goal of the project was to develop benchmarks for quantum computers that could be used to compare scientific applications on different hardware and better understand noise sources. This report will focus on work performed by researchers at Duke University.

A key challenge in benchmarking quantum computers is that the quality of individual gates does not directly translate into the quality of the overall algorithm. Correlations between the gate errors can either degrade or improve algorithmic performance. In addition, there can be side effects that result in unwanted gates on neighboring ions and dynamic effects where simultaneous gates interfere with each other.

The Duke team focused on two tasks in this project: 1) development of algorithm compilation techniques that detect and can then correct for systematic gate errors and 2) benchmarking of ion trap quantum hardware at Duke. Our compilation methods have been tested on systems at Duke, IBM, and Sandia National Laboratories. We have been able to provide a performance improvement to near-term devices as measured by algorithmic benchmarks. We provide more details about our technical work below.

Hidden inverses: a method for removing systematic gate errors

A quantum computer program is often described by a list of quantum gates and measurements ordered in time. This can be represented graphically as a quantum circuit. Any quantum computation can be constructed from one and two-qubit quantum gates. Each quantum gate corresponds to a control pulse that drives the physical dynamics of the qubit. There are multiple control pulses that will lead to the same gate.

Many canonical quantum gates are self-inverses including controlled not ($CNOT$), controlled phase (CZ), Toffoli ($CCNOT$), and Hadamard (H). This is in contrast to an arbitrary gate U whose inverse is $U^\dagger$, since all gates correspond to unitary quantum dynamics. Moreover, in many quantum hardware systems a gate such as $CNOT$ is composed of a set of native gates $CNOT = ABC$, where A, B, and C are native gates. In this framework, it is natural to define $CNOT^\dagger = C^\dagger B^\dagger A^\dagger$. Yet $CNOT = CNOT^\dagger$, so if there are no errors it should not matter which compilation we choose. It is often the case in quantum algorithms that $CNOT$s are used to transform single qubit unitary gates on the target bit into multi-qubit unitary gates on many objects. This has the form $CNOT(c,t)U_tCNOT(c,t) = V_{c,t}$ where $CNOT$ is between the control c qubit and the target t qubit. U_t is a unitary gate on the t qubit and $V_{c,t}$ is a unitary gate acting on both the control and target. From a quantum mechanics textbook point of view, it is natural to use the conjugate transpose $CNOT(c,t)^{\dagger} U_t CNOT(c,t) = V_{c,t}$

We first explored an idealized error model where the only errors are two-qubit rotation errors in the native two-qubit gate [1]. Using composite pulse techniques, we could make the residual error a single qubit Z rotation on the control. Then by using the inverted composite pulse sequence, we could create the inverted Z rotation on the next $CNOT$. The composite pulse we use suppresses the error quadratically. This idealized model allowed us to remove the systematic error an additional order in scientific quantum circuits by applying $CNOT$ and $CNOT^{\dagger}$. In current experiments, this approach does not yield better circuits. It increases the time required to perform a two-qubit gate and other types of error begin to dominate.

We then applied the approach of inverting the physical operations to create $CNOT$ and $CNOT^{\dagger}$ [3] and tested in our ion trap quantum device. This approach does not increase the time of two-qubit gates. It does require that the conjugated single qubit unitary gate U_t be close to the identity. This is a typical situation in many quantum simulation circuits.

We saw substantial improvement in circuits under two different errors: two-qubit rotation errors and frame offsets between two-qubit and single qubit gates. The correlated two-qubit rotation errors were the intended error for cancellation. It occurs due to intensity errors in the control pulses that are short compared to circuit times but long compared to a single two-qubit gate. For both one and two-qubit gates the Z operator direction is well-defined, but X and Y operators are defined relative to a phase. Unwanted systematic errors can lead to offset between these frames. We found that using hidden inverses helps reduce the circuit error due to this frame mismatch.

We saw in our experiment at Duke both improvements for overrotations and frame offsets. It also provided a new method for tuning up the system and removing the systematic error. It provided an efficient way to see the frame offset, which could then be corrected.

We then tested the hidden inverse method for scientific computation on near-term quantum instruments with our collaborators. Hidden inverses both reduce errors but can also help smooth noisy landscapes and variational quantum algorithms. Hidden inverses were highlighted theoretically in a joint work with Oak Ridge National Laboratory, Virginia Tech, and the University of Tennessee considering quantum chemistry algorithms [4]. Working with Oak Ridge National Laboratory, we tested hidden inverses on IBM cloud-based superconducting quantum computers [5] and on the ion trap quantum computer at the QSCOUT testbed at Sandia National Laboratories [6]. Hidden inverses showed advantages for converting to the correct energy for most devices it was tested on relative to standard methods and comparable performance to randomized compiling [5]. On the QSCOUT device, hidden inverses turned out to be an efficient way to both characterize and correct systematic errors [6].

Improved measurement protocols for ion trap gates

Trapped ion quantum computers create entanglement between the internal states of the ions by a mediated interaction through the common modes of motion. When assessing these gates at high-fidelity, it is necessary to repeat the gates multiple times. By repeating the basic gate, the Mølmer-Sørensen gate, multiple times we can enhance the error. It is useful to apply the gate followed by its inverse to separate the short-term systematic error that could be reduced by hidden inverses from other sources of noise. We used this technique in experiments showing high-fidelity gates with micromirrors [7], the reduction of cross-talk in ion traps [8], and the composition of different two-qubit gates to reduce error [9]. The advances in characterization of the ion trap also enabled us to use the ions to serve as an intermediary to create entanglement between the bosonic modes [10]. We also used characterization methods developed in this program to test our open-source framework for controlling quantum computers [2].

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