Measurement Noise Mitigation in a Quantum Computer Using Image Intensity Filters

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We propose a method to mitigate measurement errors in the distribution counts of a Quantum computer using image contrast filters. This work is similar to the method described by Gambetta and colleagues in [1]; however our technique does not use a linear system of equations, but an image contrast filter to mitigate the measurement noise. Furthermore this method is demonstrated against the same set of experiments described in the matrix-free measurement mitigation (M3) library from Qiskit from which [1] is based upon. Our results show our method outperforming M3 by a wide margin in all experiments. Finally, we provide results, documentation and detailed test and source code for further investigation.

I. Introduction

Contrast filters are one of the simplest methods of image adjustment to improve its quality. Image contrast enhancement refers to accentuation or sharpening of image features so as to make it more useful for visualization or analysis. The brightness of a pixel is the mean of its RGB values = (r + g + b)/3. This brightness can be increased by simply adding a delta value $\mu + \Delta\mu$ where the delta factor $\Delta\mu$ can be negative to darken the image or positive for lightning the image. We propose a method to use this simple yet powerful technique to mitigate the noise of the histogram data of an experiment by first mapping its values to probabilities; then treating those probabilities as grayscale pixels. This allows for application of image processing analysis and display techniques with the ultimate goal to mitigate or eliminate the noise altogether.

II. Method Description

Consider the first Greenberger–Horne–Zeilinger (GHZ) state describing a 3 qubit entanglement $|\psi\rangle=\frac{1}{\sqrt{2}}(|000\rangle+|111\rangle)$ (see figure 1).

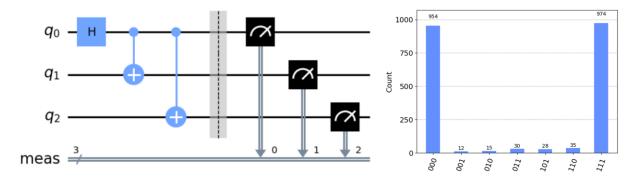


Figure 1. Experimental result of a GHZ state in IBM's 16 qubit noisy simulator FakeGuadalupe.

Take the measurement results of the experiment in figure 1 and construct a probability distribution by dividing each result count by the number of "shots" or measurements in the device; to obtain the distribution: P(X) = [0.43847, 0.50390, 0.01611, 0.00585, 0.01220, 0.01513, 0.00732, 0.00097]

We can map those probabilities to pixels in a Grayscale image. This allows for image manipulation and display. Next, apply a contrast filter to increase the separation between the darkest (low or noisy) and brightest areas of the image. The effect can be easily visualized in figure 2. Note that after the intensity rescaling step, the results need to be re-normalized resulting in a new distribution $P'(X) = [0.43454\ 0.50415\ 0.0.0.0.0.0.0]$. Finally, map the new distribution into a new set of measurement results and compare against the original (right side of figure 2).

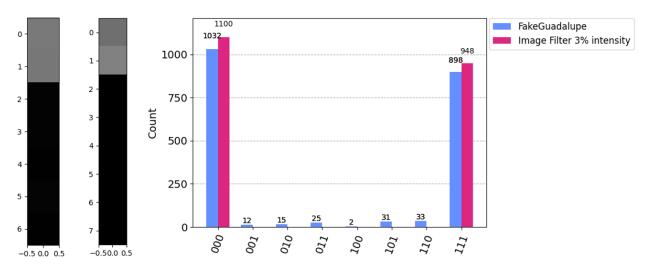


Figure 2. Visualization of the effect of brightness intensity rescaling and the final result for the GHZ state circuit in figure 1.

Note that the filter uses a desired intensity range of the input to stretch or shrink the intensity range of the image. This input range defines the Min and Max intensity values of the pixels, any value below the Min will be reduced and every value above Max will be increased. The results are encouraging enough to test this technique against the method described in [1] and implemented in the matrix-free measurement mitigation (M3) library by IBM research. Next, we run our method against the same battery of tests described in the M3 documentation.

III. Experimental Results

We follow the scalable quantum measurement error mitigation tests described by the *mthree* library; and just like *mthree*, this method only works for tasks using quasi-probabilities such as sampling problems, and expectation value estimation.

1. Probability Mitigation

We updated the experiment in [11] designed to correct readout errors and transform the outcomes to a true probability distribution. The experiment runs in the 14 qubit noisy simulator FakeMelbourne and shows the circuit and probability distributions for the raw device, M3 and image intensity mitigation at an input range of 3% (0.03, 0.97) (see figure 3).

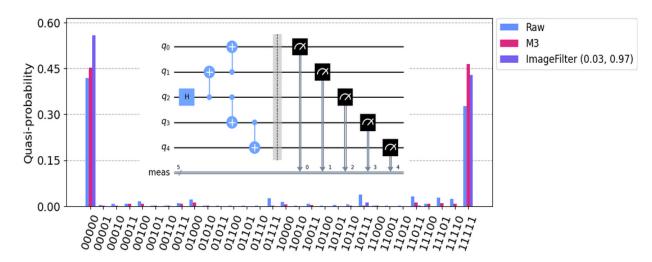


Figure 3. Experimental results for readout error correction in FakeMelbourne, modified from [11].

Our technique clearly outperforms M3 by a wide margin. These are solid and encouraging results and the first step in a battery of tests to demonstrate the feasibility of this technique. Next we measure against M3's sampling experiments which yield even better outcomes.

2. Sampling Mitigation with Bernstein Vazirani (BV)

This is the mitigation test by sampling using Bernstein Vaziriani circuits of multiple lengths described in [2]. The test generates BV circuits for all-ones bit-strings of various lengths (see figure 4), and transpiles them against the 27 qubit noisy simulator FakeKolkata. This is an excellent test for mitigation techniques as the noise accrues when the number of Control-X gates increases.

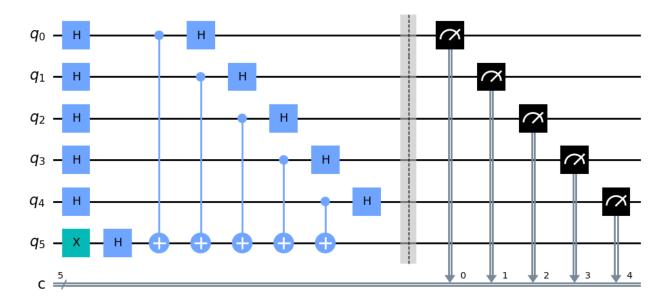


Figure 4. 5-qubit Bernstein-Vazirani circuit from the sampling mitigation test in [2].

We follow the test carefully, only altering the test code to insert the filter mitigation technique with intensity ranges of 1% [Input range (0.01, 0.99)] and 2% [Input range (0.02, 0.98)]. The success probability is displayed for the raw (unmitigated), M3 mitigated, and (1%, 2%) intensity levels (see figure 5).

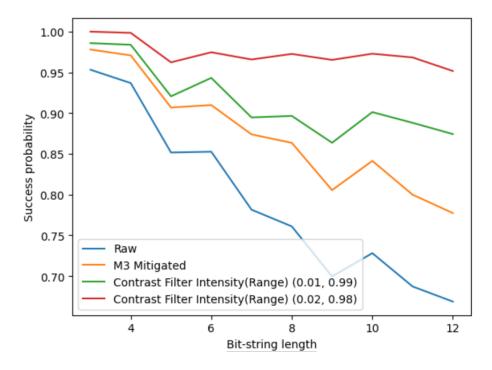


Figure 5. Mitigation experiment results for BV circuits of various lengths using M3.

The results show the intensity filter technique outperforming M3 by a solid margin for a 2% intensity level; even at 1% it produces better results. Furthermore, due to its simplicity, image manipulation filtering performs faster than the system of linear equations used by M3. The next test demonstrates correcting mid-circuit measurements using the dynamic version of the Bernstein-Vazirani algorithm.

3. Dynamic Bernstein-Vazirani

The dynamic Bernstein-Vazirani algorithm test uses Qiskit's sophisticated mid-circuit measurements and conditional resets to showcase M3's measurement error correction [3]. This reduces the number of qubits significantly by allowing the same qubit to be reused after each partial measurement (see figure 6). Note that the depth of the circuit will increase along with the bit strength which may affect the overall execution time. The experiment is run with the following parameters and the results are shown in figure 7.

• Device: 27 qubit noisy simulator FakeKolkata.

• Measurement shots: 10000.

• Qubit strengths: 2-31.

• Mitigation: M3 vs Intensity filter at 1% input range of (0.01,0.99).

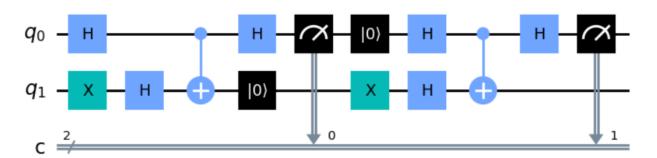


Figure 6. Dynamic Bernstein-Vazirani circuit for 2 qubits.

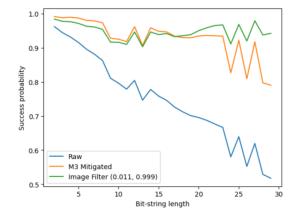


Figure 7. Experimental results for dynamic BV circuits at multiple bit strengths.

Once again, after a simple modification of this test to include our technique, the result shows the intensity filter outperforming M3 as the number of qubits increases even at a low intensity level of 1%. Furthermore, by increasing this level the noise can be virtually eliminated. In the next test, we measure against an experiment that is not part of the official M3 documentation, but the resilience mechanism implemented by IBM at the quantum level. Our technique shows excellent results against quantum resilience.

4. Quantum Resilience using Trotterization

This experiment showcases the error suppression and mitigation at the quantum level built into the Qiskit Runtime [4]. In practice, it can be hard to compute eigen-functions for time dependent Hamiltonian operators; hence a technique called Trotterization is used to segment an exponentiated matrix into a series of smaller exponentiated matrices with minimal error. This method reduces the complexity by providing an estimate of the solution to the time-dependent Hamiltonian. For a detailed description of this technique see [5]. Qiskit runtime implements three levels of Quantum resilience:

- 1. Twirled readout error extinction (T-Rex): It is a general and effective technique to reduce measurement noise by attaching extra measurement and calibration circuits for the estimation of error mitigated averages [6].
- 2. Zero Noise Extrapolation (ZNE): It works by first amplifying the noise in the circuit of the desired quantum state, obtaining measurements for several different levels of noise, and using those measurements to infer the noiseless result [7].
- 3. Probabilistic error cancellation (PEC): It samples for a collection of circuits that mimic a noise inverting channel to cancel out the noise in the desired computation similar to the way noise canceling headphones work [7].

We altered the experiment to include the intensity filtering technique with the results shown in figure 8. Our technique outperforms T-Rex and ZNE by a wide margin, and arguably does better than PEC (bottom of figure 7). It should be noted that, although PEC performs the best among the quantum resilience techniques, it has a sampling overhead time complexity in the exponential level to the number of gates. As a matter of fact, by the time of this writing, if you run an experiment using PEC resilience and your circuit has more than 10 Control-X gates, your experiment may crash after multiple hours.

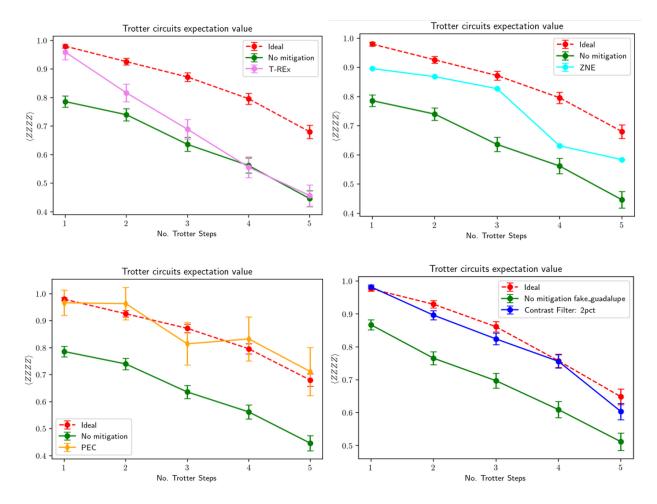


Figure 8. Results for the quantum resilience experiment using Trotterization circuits described in [5]. From the top left T-Rex, ZNE, PEC and image intensity filtering at 2% input range.

5. Basic Variational Quantum EigenSolver (VQE)

This test is described in [8]. It takes the sample Hamiltonian H = 0.3979YZ - 0.3979ZI - 0.01128ZZ + 0.1809XX and calculates the expected energy value using the following VQE state preparation:

- Ansatz: *TwoLocal* from Qiskit library with full entanglement (each qubit is entangled with all the others).
- Measurement circuits: Created by moving the observables in the Hamiltonian (YZ, ZI, ZZ,XX) into the computational basis by appending an Hadamard Gate (H) to each Pauli X gate, and a S-dagger and H for each Y gate in the observable (Z, I remain unchanged) as shown in figure 9.
- Initial parameter angles: [1.22253725, 0.39053752, 0.21462153, 5.48308027, 2.06984514, 3.65227416, 4.01911194, 0.35749589]

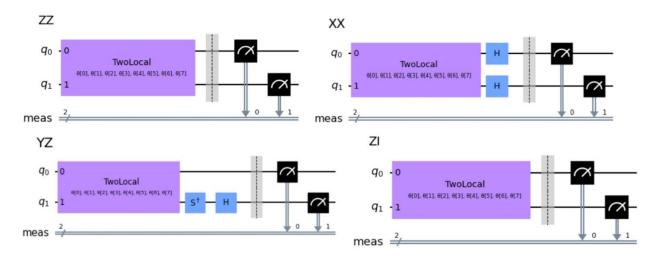


Figure 9 Measurement circuits for the VQE experiment in [8].

The image intensity filter method performs better than M3, yielding a more accurate estimate of the final energy of the Hamiltonian:

M3 Mitigation Results

• Energy: -0.4248273342124237

• Angles: [1.25560585 0.38654154 0.20846952 5.48743517 2.03181833 3.68814594 3.91540956 0.36953303]

Image Intensity Filter Results at 1% input range (0.01,0.99)

• Energy: -0.43324214733405414

• Angles: [1.23757107 0.4211179 0.08658293 5.49275181 2.05102127 3.67389758 4.03722484 0.3746737]

The optimal solution is defined in [8]: -0.44841884382998787.

6. Ising Models using VQE

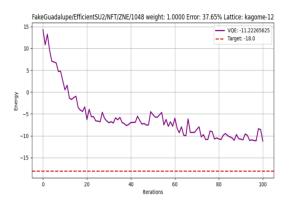
For the final test, we chose the state preparation for the Kagome lattice using the VQE. This experiment was part of the IBM's Open Science Prize 2022. The challenge amounts to preparing the frustrated ground state of a Heisenberg spin-1/2 model on a Kagome lattice using the VQE algorithm. A basic notebook was provided by IBM for participants to do their work. We used this code to test the behavior of our method with encouraging results. The state as chosen for this experiment consists of:

• Hamiltonian: The antiferromagnetic Heisenberg model arranged on a Kagome lattice

$$H = \sum_{i,j} X_i X_j + Y_i Y_j + Z_i Z_j$$

- Ansatz: EfficientSU2 a circuit made of layers of single qubit operations spanned by Unitary-Set-Dimension2 SU(2) and Controlled-X entanglements from Qiskit library. This is a heuristic pattern that can be used to prepare trial wave functions for quantum algorithms or classification circuits for machine learning. The default entanglement is set to reverse_linear as it provides fewer entangling gates than the rest.
- Backend: The 16-qubit noisy simulator FakeGuadalupe which closely mirrors IBM's hardware device ibmq_guadalupe.
- Optimizer: Nakanishi-Fujii-Todo algorithm from Qiskit library; the maximum number of iterations to perform defaults to 100.
- Shots or number of measurements in the experiment: 2048.
- The expected ground state: -18.

Because code modifications for this experiment require changes to the Qiskit runtime service, we were unable to run in a real device; however with a modified version of Qiskit's *BackendEstimator* class we injected our mitigation logic in the code. The results are presented in figure 10.



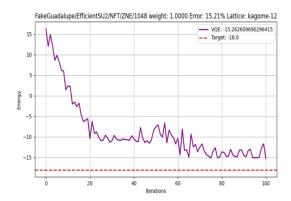


Figure 10. Experimental results for the ground state preparation of the Kagome lattice; the metric of performance in the challenge judging criteria if given by the relative difference between the expected ground state (-18.0) and the VQE result.

The left side of figure 9, shows the unmitigated ground state with a relative error of 37.6%, on the right side the intensity filter mitigated at 2%% (0.002-0.998) result showing a slim improvement at 15.2% relative error. This result is a bit disappointing as we expected better performance nevertheless a noise reduction of 15 percentage points is remarkable.

IV. Conclusion

We developed a method to mitigate measurement errors in the distribution counts of a Quantum computer using image contrast filters at various input ranges. This technique was extensively tested against IBM's de-facto mitigation library M3 with remarkable results. Our

method outperformed M3 by wide margins in all tests. We also tested against IBM's quantum resilience (T-Rex, ZNE and PEC) with equally excellent outcomes. In this age of noisy quantum computers, error mitigation has become a prime area of research. It is critical to develop an efficient and fast method to eliminate noise from measurement outcomes. At the quantum level, there are a myriad of resilience techniques, error correction codes, and other methods; however, these approaches require an excessive number of ancillary qubits and furthermore contribute to the overall noise themselves. We believe, at this stage, noise can be managed at the classical level with a fast and efficient technique, and our method is a solid step in that direction. It outperforms the top implementations by IBM. The results speak for themselves.

V. Source Code

Detailed implementations for each experiment is available for download from GitHub at https://github.com/Shark-y/quantum_mitigation

VI. References

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