The Journal of Open Source Software

QuantumACES.jl: design noise characterisation experiments for quantum computers

Evan T. Hockings [1,2]

1 School of Physics, The University of Sydney, Sydney, NSW 2006, Australia **2** ARC Centre of Excellence for Engineered Quantum Systems

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor: Open Journals

Reviewers:

- @openjournals

Submitted: 01 January 1970
Published: unpublished

Summary

QuantumACES is a Julia (Bezanson et al., 2017) package for designing, simulating, and performing scalable Pauli noise characterisation experiments for quantum computers. Noise in quantum devices is the key obstacle to large-scale quantum computation. Consequently, quantum computers will require fault-tolerant architectures that replace physical qubits and operations with redundantly-encoded logical equivalents, which entails regularly measuring the parity checks of quantum error correcting codes (Aliferis, 2013; Gottesman, 2010; Shor, 1996). Decoders process the resulting error syndrome data and attempt to infer the most likely underlying physical errors in the quantum device. Subsequently, they determine correction operations that attempt to preserve logical information. The noise estimates produced by QuantumACES can inform decoders of the likelihood of physical error configurations in a quantum device (Chen et al., 2022; Higgott et al., 2023; Sundaresan et al., 2023; Tiurev et al., 2023; Tuckett et al., 2020), enabling noise-aware decoding. They can also be used to generate simulated data for training more accurate decoders, such as (Bausch et al., 2024), verify appropriate device calibration, and inform the co-design of quantum error correcting codes, decoders, fault-tolerant circuits, and quantum devices.

QuantumACES designs experiments to characterise Pauli noise in stabiliser circuits within the framework of averaged circuit eigenvalue sampling (ACES) (Flammia, 2022), following the theory and protocol outlined in (Hockings et al., 2025b). Stabiliser circuits are a restricted class of quantum circuits that admit efficient classical simulation (Aaronson & Gottesman, 2004; Gottesman, 1997), including with Pauli noise. Quantum noise is tailored into Pauli noise by techniques such as Pauli frame randomisation (Knill, 2005), randomised compiling (Wallman & Emerson, 2016), or quantum error correction itself (Beale et al., 2018). Additionally, the theory of quantum error correction and fault tolerance generally relies on modelling noise as Pauli noise (Terhal, 2015).

QuantumACES contains routines for optimising designs for noise characterisation experiments, given an arbitrary stabiliser circuit and Pauli noise model, using functions that precisely predict the performance of these experimental designs. It has built-in circuits and noise models and also allows users to define their own. These noise characterisation experiments are simulated with the open-source Python package Stim (Gidney, 2021), a fast simulator for stabiliser circuits with Pauli noise.

In a typical fault-tolerant quantum computing architecture, the bulk of the physical qubits and gate operations are dedicated to performing the syndrome extraction circuits that measure the parity checks of quantum error correcting codes. These syndrome extraction circuits, which are stabiliser circuits, are therefore the key target for noise characterisation experiments. QuantumACES is tailored to characterising Pauli noise in syndrome extraction circuits, particularly for topological quantum error correcting codes such as the surface code (Bravyi & Kitaev, 1998; Dennis et al., 2002; Fowler et al., 2012; Kitaev, 2003). It leverages the fact that the simple

structures of the syndrome extraction circuits of topological quantum codes remain similar across code sizes. This enables optimised large-scale noise characterisation experiments that use experimental designs optimised at small scales. QuantumACES is capable of calculating and precisely fitting the performance scaling of these experimental designs as a function of the code size, enabling performance predictions at scales where explicit calculation becomes intractable.

Moreover, QuantumACES supports the simulation and decoding of memory experiments for syndrome extraction circuits with Stim and the open-source Python packages PyMatching (Higgott, 2022; Higgott & Gidney, 2025) and BeliefMatching (Higgott et al., 2023), respectively. It also provides an interface with the open-source Python package Qiskit (Javadi-Abhari et al., 2024), enabling the export of experimental designs to Qiskit circuits that can then be implemented to characterise noise in real quantum devices.

Statement of need

The utility of detailed and scalable Pauli noise characterisation methods grows as experimental progress pushes quantum devices towards scales of hundreds of qubits and initial demonstrations of fault tolerance. QuantumACES enables noise characterisation and noise-aware decoding in this context, as demonstrated in (Hockings et al., 2025b) and (Hockings et al., 2025a), respectively. While there are several software packages for benchmarking and noise characterisation, there are no open-source packages capable of detailed and scalable Pauli noise characterisation of quantum devices. Forest-Benchmarking (Combes et al., 2019) is an open-source Python package containing many routines for quantum characterisation, verification, and validation (QCVV), but its detailed noise characterisation techniques are not scalable. Gate set tomography (GST) (Nielsen et al., 2021) is a principled and extremely detailed noise characterisation protocol implemented by the open-source Python package pyGSTi (Nielsen et al., 2022), but it is limited to characterising very small numbers of qubits. Cycle error reconstruction (CER) (Carignan-Dugas et al., 2023) is the noise characterisation protocol whose capabilities are most similar to ACES, but it is implemented by the commercial software True-Q (Beale et al., 2020).

Acknowledgements

This work was supported by the Australian Research Council Centre of Excellence for Engineered Quantum Systems (CE170100009), the U.S. Army Research Office (W911NF-21-1-0001, W911NF-23-S-0004), and the Unitary Foundation.

References

Aaronson, S., & Gottesman, D. (2004). Improved simulation of stabilizer circuits. *Physical Review A*, *70*(5), 052328. https://doi.org/10.1103/PhysRevA.70.052328

Aliferis, P. (2013). Introduction to quantum fault tolerance. In D. A. Lidar & T. A. Brun (Eds.), *Quantum Error Correction* (pp. 126–160). Cambridge University Press. https://doi.org/10.1017/CBO9781139034807.007

Bausch, J., Senior, A. W., Heras, F. J. H., Edlich, T., Davies, A., Newman, M., Jones, C., Satzinger, K., Niu, M. Y., Blackwell, S., Holland, G., Kafri, D., Atalaya, J., Gidney, C., Hassabis, D., Boixo, S., Neven, H., & Kohli, P. (2024). Learning high-accuracy error decoding for quantum processors. *Nature*, *635*(8040), 834–840. https://doi.org/10.1038/s41586-024-08148-8

Beale, S. J., Boone, K., Carignan-Dugas, A., Chytros, A., Dahlen, D., Dawkins, H., Emerson, J., Ferracin, S., Frey, V., Hincks, I., Hufnagel, D., Iyer, P., Jain, A., Kolbush, J., Ospadov, E., Pino, J. L., Qassim, H., Saunders, J., Skanes-Norman, J., … Wright, E. (2020). *True-Q*. Zenodo. https://doi.org/10.5281/zenodo.3945249

Beale, S. J., Wallman, J. J., Gutiérrez, M., Brown, K. R., & Laflamme, R. (2018). Coherence in quantum error-correcting codes. *Physical Review Letters*, *121*(19), 190501. https://doi.org/10.1103/PhysRevLett.121.190501

Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to numerical computing. *SIAM Review*, *59*(1), 65–98. https://doi.org/10.1137/141000671

Bravyi, S. B., & Kitaev, A. Y. (1998). Quantum codes on a lattice with boundary. *arXiv Preprint*. https://arxiv.org/abs/quant-ph/9811052

Carignan-Dugas, A., Dahlen, D., Hincks, I., Ospadov, E., Beale, S. J., Ferracin, S., Skanes-Norman, J., Emerson, J., & Wallman, J. J. (2023). The error reconstruction and compiled calibration of quantum computing cycles. *arXiv Preprint*. https://arxiv.org/abs/2303.17714

Chen, E. H., Yoder, T. J., Kim, Y., Sundaresan, N., Srinivasan, S., Li, M., Córcoles, A. D., Cross, A. W., & Takita, M. (2022). Calibrated decoders for experimental quantum error correction. *Physical Review Letters*, *128*(11), 110504. https://doi.org/10.1103/PhysRevLett.128.110504

Combes, J., Gulshen, K. V., Harrigan, M. P., Karalekas, P. J., Silva, M. P. da, Alam, M. S., Brown, A. F., Caldwell, S., Capelluto, L. C., Crooks, G. E., Girshovich, D., Johnson, B. R., Peterson, E. C., Polloreno, A. M., Rubin, N. C., Ryan, C. A., Staley, A. N., Tezak, N. A., & Valery, J. A. (2019). *Forest benchmarking: QCVV using PyQuil*. Zenodo. https://doi.org/10.5281/zenodo.3455848

Dennis, E., Kitaev, A., Landahl, A., & Preskill, J. (2002). Topological quantum memory. *Journal of Mathematical Physics*, *43*(9), 4452–4505. https://doi.org/10.1063/1.1499754

Flammia, S. T. (2022). Averaged circuit eigenvalue sampling. *17th Conference on the Theory of Quantum Computation, Communication and Cryptography*, *232*, 4:1–4:10. https://doi.org/10.4230/LIPIcs.TQC.2022.4

Fowler, A. G., Mariantoni, M., Martinis, J. M., & Cleland, A. N. (2012). Surface codes: Towards practical large-scale quantum computation. *Physical Review A*, *86*(3), 032324. https://doi.org/10.1103/PhysRevA.86.032324

Gidney, C. (2021). Stim: A fast stabilizer circuit simulator. *Quantum*, *5*, 497. https://doi.org/10.22331/q-2021-07-06-497

Gottesman, D. (1997). *Stabilizer codes and quantum error correction* [PhD thesis, California Institute of Technology]. https://doi.org/10.7907/rzr7-dt72

Gottesman, D. (2010). An introduction to quantum error correction and fault-tolerant quantum computation. In S. Lomonaco (Ed.), *Quantum information science and its contributions to mathematics* (Vol. 68, pp. 13–58). American Mathematical Society. https://doi.org/10.1090/psapm/068

Higgott, O. (2022). PyMatching: A Python package for decoding quantum codes with minimum-weight perfect matching. *ACM Transactions on Quantum Computing*, *3*(3), 16:1–16:16. https://doi.org/10.1145/3505637

Higgott, O., Bohdanowicz, T. C., Kubica, A., Flammia, S. T., & Campbell, E. T. (2023). Improved decoding of circuit noise and fragile boundaries of tailored surface codes. *Physical Review X*, *13*(3), 031007. https://doi.org/10.1103/PhysRevX.13.031007

Higgott, O., & Gidney, C. (2025). Sparse blossom: Correcting a million errors per core second with minimum-weight matching. *Quantum*, *9*, 1600. https://doi.org/10.22331/q-2025-01-20-1600

Hockings, E. T., Doherty, A. C., & Harper, R. (2025a). *Improving error suppression with* *noise-aware decoding*. https://arxiv.org/abs/2502.21044

Hockings, E. T., Doherty, A. C., & Harper, R. (2025b). Scalable noise characterisation of syndrome extraction circuits with averaged circuit eigenvalue sampling. *PRX Quantum*, *6*(1), 010334. https://doi.org/10.1103/PRXQuantum.6.010334

Javadi-Abhari, A., Treinish, M., Krsulich, K., Wood, C. J., Lishman, J., Gacon, J., Martiel, S., Nation, P. D., Bishop, L. S., Cross, A. W., Johnson, B. R., & Gambetta, J. M. (2024). Quantum computing with Qiskit. *arXiv Preprint*. https://arxiv.org/abs/2405.08810

Kitaev, A. Y. (2003). Fault-tolerant quantum computation by anyons. *Annals of Physics*, *303*(1), 2–30. https://doi.org/10.1016/S0003-4916(02)00018-0

Knill, E. (2005). Quantum computing with realistically noisy devices. *Nature*, *434*(7029), 39–44. https://doi.org/10.1038/nature03350

Nielsen, E., Gamble, J. K., Rudinger, K., Scholten, T., Young, K., & Blume-Kohout, R. (2021). Gate set tomography. *Quantum*, *5*, 557. https://doi.org/10.22331/q-2021-10-05-557

Nielsen, E., Seritan, S., Proctor, T., Rudinger, K., Young, K., Russo, A., Blume-Kohout, R., Kelly, R. P., Gamble, J. K., & Saldyt, L. (2022). *pyGSTi*. Zenodo. https://doi.org/10.5281/zenodo.594712

Shor, P. W. (1996). Fault-tolerant quantum computation. *Proceedings of the 37th Annual Symposium on Foundations of Computer Science*, 56–65. https://doi.org/10.1109/SFCS.1996.548464

Sundaresan, N., Yoder, T. J., Kim, Y., Li, M., Chen, E. H., Harper, G., Thorbeck, T., Cross, A. W., Córcoles, A. D., & Takita, M. (2023). Demonstrating multi-round subsystem quantum error correction using matching and maximum likelihood decoders. *Nature Communications*, *14*(1), 2852. https://doi.org/10.1038/s41467-023-38247-5

Terhal, B. M. (2015). Quantum error correction for quantum memories. *Reviews of Modern Physics*, *87*(2), 307–346. https://doi.org/10.1103/RevModPhys.87.307

Tiurev, K., Derks, P.-J. H. S., Roffe, J., Eisert, J., & Reiner, J.-M. (2023). Correcting non-independent and non-identically distributed errors with surface codes. *Quantum*, *7*, 1123. https://doi.org/10.22331/q-2023-09-26-1123

Tuckett, D. K., Bartlett, S. D., Flammia, S. T., & Brown, B. J. (2020). Fault-tolerant thresholds for the surface code in excess of 5% under biased noise. *Physical Review Letters*, *124*(13), 130501. https://doi.org/10.1103/PhysRevLett.124.130501

Wallman, J. J., & Emerson, J. (2016). Noise tailoring for scalable quantum computation via randomized compiling. *Physical Review A*, *94*(5), 052325. https://doi.org/10.1103/PhysRevA.94.052325