Usage Report for Fiscal Year 2021

Project Title:

Simulation-based Learning for Open Quantum Systems

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1. Background and purpose of the project, relationship of the project with other projects

We set out to study how to make a more robust and efficient sensing device using the dynamics of quantum systems near criticality. We utilize the criticality of an open (dissipative) quantum system, along the lines of the "critical parametric quantum sensing" protocol using a two-photon Kerr resonator: this protocol can be very sensitive to the state of a qubit by accessing the number of photons inside the cavity during the dissipative dynamics (a spin-up state leads to very few photons, while a spin-down state leads to many photons).

The sensing protocol can be enhanced by accessing all the critical fluctuations of the dynamics. While this is challenging to do with pen and paper (requiring non-trivial computations of spectral properties of the Liouvillian generator), we know that machine learning methods can efficiently be used to extract signal from large datasets, even in the presence of experimental noise.

2. Specific usage status of the system and calculation method

We have used single-node, multi-threaded python code based on QuTiP and Scikit-Learn on Hokusai BIGWATERFALL. The cluster has been used for the two main steps of the calculation:

1. Simulating the quantum trajectories of the superconducting qubit coupled to a resonator cavity in a large parameter space (we imagine a circuit-QED implementation where a driven resonator is coupled to a SQUID element and we explore the effects of different detuning and drive intensities)
2. Analyzing the dataset created from the quantum trajectories for a variety of cuts to the dynamics and a variety of machine learning models (we explore both tabular models and time series models)

The numerical simulations are based on QuTiP and they realize critical fluctuations seen in actual experimental dynamical systems of this kind. Each set of parameters for the system, a pair of detuning and drive intensity values, is simulated for a long time in order to reach the steady state from two initial conditions of the superconducting qubit, corresponding to the spin-up and spin-down states.

The machine learning analysis is based on Scikit-Learn models that are simple to interpret, such as linear regression with a few hand-picked features extracted from the dynamics of the simulated measurements. We start from two baseline models using two different features, the average (MEAN) and the standard deviation (STD) over the whole dynamics of the absolute value of the observable. These two features are then fed into linear unregularized logistic regression models.

We then move on to explore non-linear models with a variety of features. In particular, we focus on support vector machine classifiers based on two set of features. The first set is simply given by the values of the observable at each time during the dynamics (all time points are considered independent). The second set is constructed from random time intervals during the dynamics by calculating summary statistics such as the mean, the variance, or the slope of the observable in such interval.

３． Result

We have obtained very promising results by studying the aforementioned machine learning models applied to the dynamics of an ideal superconducting qubit coupled to a readout cavity resonator. By computing the accuracy of the machine learning methods for various choices of the dataset (short measurements, long measurements, averaged measurements, etc..) we have demonstrated that:

1. There is an optimal region of the parameter space of the resonator near the phase transition where the accuracy has a maximum
2. There is an optimal measurement time at which the machine learning models can achieve a very high accuracy

４． Conclusion

Our project demonstrates that machine learning methods can be used to increase the efficiency of readout procedures for current state-of-the-art superconducting qubits, viewed as dissipative open quantum systems near a critical phase transition.

５． Schedule and prospect for the future

We expect to continue this project in the next fiscal year and study the effects of dissipation on the qubit, in addition to the cavity. Moreover, we will add a study of the effects of real instrumental noise on our procedure.

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Fiscal Year 2021 List of Publications Resulting from the Use of the supercomputer

[Conference Proceedings]

Enrico Rinaldi, Roberto Di Candia, Simone Felicetti, Fabrizio Minganti, “Dispersive qubit readout with machine learning”, 4th workshop on Machine Learning and the Physical Sciences at NeurIPS 2021, December 13th

[Poster presentation]

Enrico Rinaldi, “Dispersive qubit readout with machine learning”, 4th workshop on Machine Learning and the Physical Sciences at NeurIPS 2021, December 13th