Invited Paper

# Machine-learning enhanced quantum state tomography and quantum noise reduction to the advanced gravitational wave detectors

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## ABSTRACT

With this talk, I will first illustrate the implementation of our machine-learning (ML) enhanced quantum state tomography (QST) for continuous variables, through the experimentally measured data generated from squeezed vacuum states, as an example of quantum machine learning. At the same time, as a collaborator for LIGO-Virgo-KAGRA (LVK) gravitational wave network and Einstein Telescope, our plan to inject this squeezed vacuum field into the advanced gravitational wave detectors (GWD) will be introduced. Finally, I will report our recent progress in applying such a ML-QST as a crucial diagnostic toolbox for applications with squeezed states, from Wigner currents, optical cat state generation, and Bayesian estimation for GWD.

**Keywords:** Quantum Noise Squeezing, Quantum State Tomography, Gravitational Wave Detector, Quantum Machine-Learning

## 1. INTRODUCTION

Due to unavoidable coupling from the noisy environment, the capability to precisely characterize the quantum features in a large Hilbert space is needed. In general, the reconstruction is not in the quantum state, but the corresponding density matrix as the degradation transforms the target quantum state into a mixed state. For continuous variables with infinite dimensions, by utilizing quantum homodyne measurements, quantum state tomography (QST) has provided us with a useful tool for reconstructing quantum states.[1,2]

By estimating the closest probability distribution to the data, the maximum likelihood estimation (MLE) method is one of the most popular methods in reconstructing arbitrary quantum states. However, MLE suffers from the overestimation problem as the required amount of measurements to reconstruct the quantum state exponentially increases with the number of involved modes. However, in dealing with continuous variables, even truncating the Hilbert space into a finite dimension, a very large amount of data are still needed in reconstructing a truncated density matrix. In this talk, instead of training the machine on the reconstruction model, alternatively, we develop a characteristic model-based machine-learning (ML)-QST by skipping the training on the truncated density matrix. Such a characteristic model-based ML-QST can avoid the problem of dealing with large Hilbert space but keep feature extraction with high precision.[3]

## 2. MACHINE-LEARNING ENHANCED QUANTUM STATE TOMOGRAPHY

As illustrated in Figure 1, by feeding noisy data of a quadrature sequence acquired by quantum homodyne tomography into 17 convolutional layers, we take advantage of good generalizability in applying CNN. In our one-dimensional (1D)-CNN kernel, there are five convolution blocks used, each of which contains two convolution layers (filters) in different sizes. In order to tackle the gradient vanishing problem, which commonly happens in the deep CNN when the number of convolution layers increases, some shortcuts are also introduced among the convolution blocks. Nevertheless, after flattening the 1D-CNN kernel, we either apply extra fully connected layers to reconstruct the truncated density matrix (coined as the reconstructed model) or predict physical parameters directly (coined as the characteristic model). The details and differences in the reconstruction model and characteristic modes will be described in my talk, as one example of quantum machine-learning.[4]

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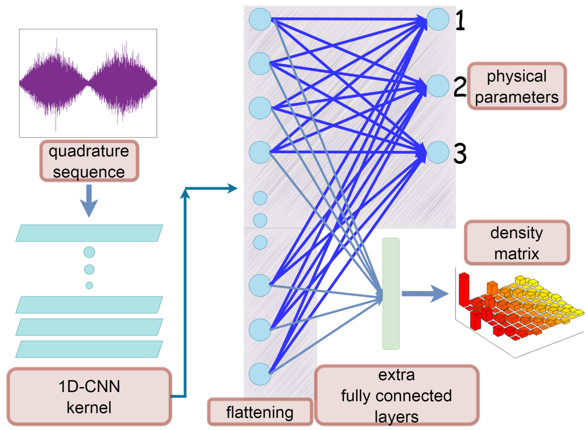


Figure 1. Demonstration of direct parameter estimations with machine learning. Here, in a single-scan measurement of the LO phase, the noisy data of quadrature sequence obtained by quantum homodyne tomography are fed to the convolutional layers, denoted as a 1D-CNN kernel.

## 3. QUANTUM NOISE REDUCTION TO THE ADVANCED GRAVITATIONAL WAVE DETECTORS

For broadband quantum noise reduction of gravitational-wave detectors, frequency-dependent squeezed vacuum (FDSQZ) is the most promising technique and will be implemented in Advanced LIGO, Advanced Virgo and KAGRA.[5] Here, by developing machine-learning (ML) enhanced quantum state tomography (QST) for squeezed states, we applied this ML-QST as a crucial diagnostic toolbox for the advanced gravitational wave detectors.

With the benefits from the good properties of the Gaussian states, including vacuum and squeezed states, a neural network can directly analyze the raw data to obtain the first and second moments of probability density function. Nevertheless, difficulties arise for such a relatively simple prediction map when non-Gaussian states are attacked. One may increase the number of neurons in dealing with non-Gaussian states, however the training process tends to cause overfitting problem. Here, we report a neural network enhanced state tomography for non-Gaussian states. Moreover, this fast and easy-to-install methodology helps us with a better understanding on quantum optics experiments with non-Gaussian states, such as photon-added squeezed states.[6]

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## REFERENCES

[1] Hsien-Yi Hsieh, et al., "Extract the Degradation Information in Squeezed States with Machine Learning," Phys. Rev. Lett. 128, 073604 (2022).
[2] Yi-Ru Chen, et al., "Experimental reconstruction of Wigner phase-space current," Phys. Rev. A 108, 023729 (2023).
[3] Hsien-Yi Hsieh, et al., "Direct parameter estimations from machine-learning enhanced quantum state tomography," Symmetry 14, 874 (2022).
[4] Alexey Melnikov, Mohammad Kordzanganeh, Alexander Alodjants, and Ray-Kuang Lee," Quantum Machine Learning: from physics to software engineering," Adv. in Phys. X (Review Article) 8, 2165452 (2023).
[5] Yuhang Zhao, et al., "Frequency-dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors," Phys. Rev. Lett. 124, 171101 (2020).
[6] Yi-Ru Chen, et al., "Generation of heralded optical 'Schroedinger cat' states by photon-addition," [arXiv: 2306.13011].