Machine Learning for Quantum Storage in Cold Atoms

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Introduction

Quantum storage is an essential technology in quantum communication, enabling the storage and retrieval of quantum bits on demand for quantum information processing. In atomic ensemble-based quantum storage, one of the main challenges is improving storage efficiency which is closely related to the optical depth of the system. However, quantum storage in cold atomic ensemble is controlled by multiparameter setting in actual experiments which presents challenges for enhancing the optical depth.

When the laser field with angular frequency ω and wave vector k transmit through the medium with the length L and one-order linear susceptibility χ, the output electrical field is expressed as

$$E_{out} = E_{in} e^{i\frac{\chi(w)}{2}k_0 L}$$

and the transmitted light intensity can be expressed as

$$I_{out} = \frac{1}{2} c\varepsilon_0 |E_{out}|^2 = I_{in} e^{-Im\{\chi\}k_0 L} = I_{in} e^{-OD}$$

where OD defined as optical depth is a key metric for evaluating atom-light coupling strength.

One of the most common used cold atomic systems is magneto-optical trap (MOT) which provides an interface for manipulating the interaction of light and atoms, as shown in Fig.1a. The precise control of cold atom systems requires the regulation of multi-parameter experimental settings, which introduces challenges in optimizing system performance. Recently, online optimization experiments combined with machine learning techniques have successfully shown a potential to enhance system performance beyond traditional human strategy in quantum control, which has emerged as an efficient means to develop empirical models of complex systems.

In the present work, we aim to optimize the optical depth of a cold atomic ensemble based on a feedback-driven online procedure. The algorithm named M-LOOP is given control over a set of experimental parameters, which is adjusted to optimize system performance.[1] As shown in the figure, we employ three independent artificial neural networks (ANNS) that collectively form a stochastic artificial neural network (SANN). For such systems, optimization through an algorithmic process designed to minimize the cost function can explore solution sets that can highly outperform traditional solution sets. Our approach is computationally efficient enough to optimize a system with a large number of control parameters in real-time.[2]

Experimental Setup & Results

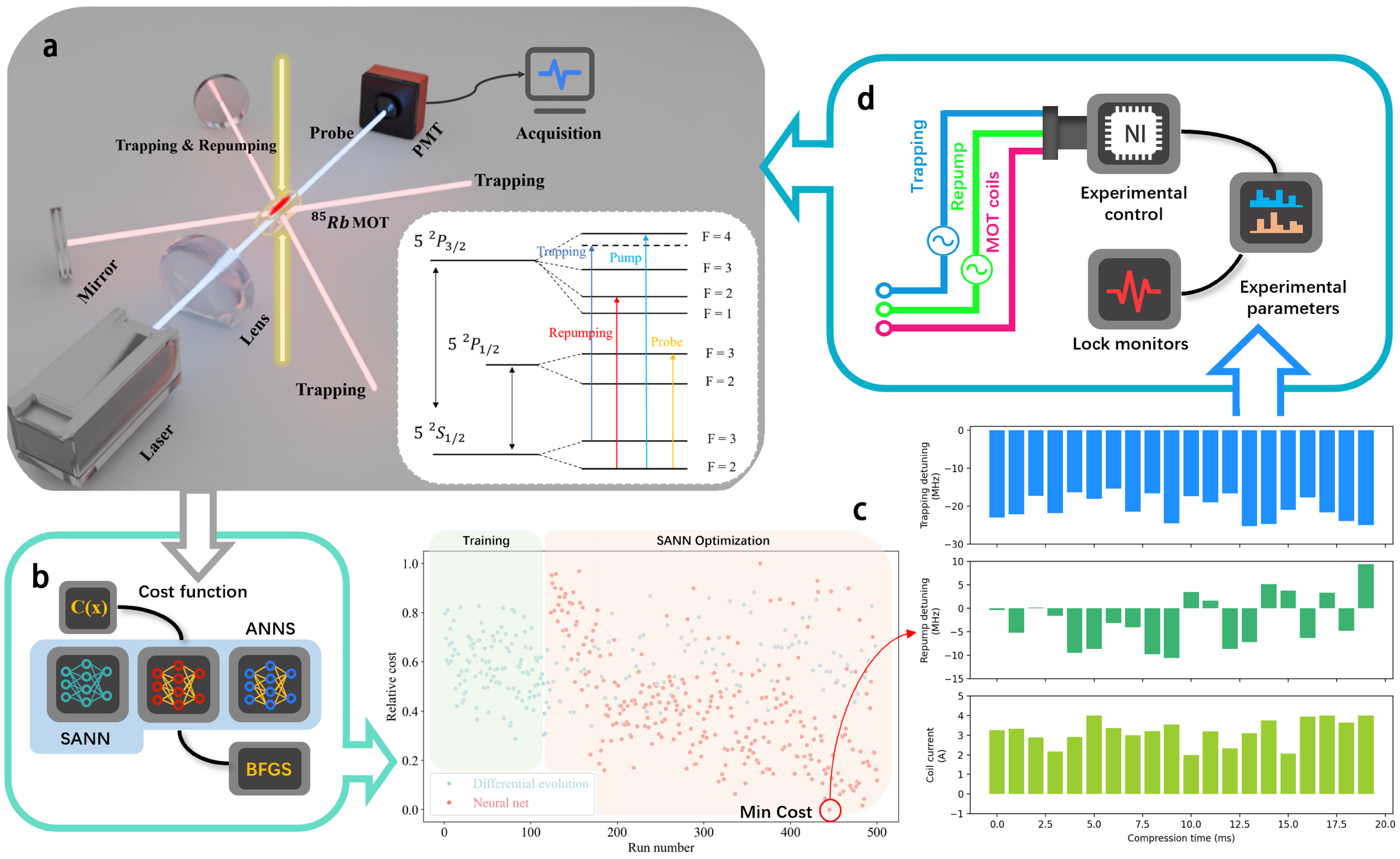

Figure 1: Online optimisation of optical depth. **a.** Magneto-optical trap setup.A detuned probe beam with sweeping frequency collected from photomultiplier tube (PMT) is transmitted through the atomic ensemble for measuring OD. **b.** The real-time measurement results and calculated cost function are feedback into the optimization training algorithm to generate the next set of parameters. Each ANN that comprises the SANN is trained using the measurement result and the previous training data. Each ANN generates a parameter set by minimising the predicted cost landscape using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm. **c.** The compression stage in time sequence in traditional compression time sequence is selected for parameter optimization. There are 60 parameters for optimization in total. **d.** The new generated parameter set is delivered to the actual experimental control when the monitor system shows that the system is stable and normal.

Follow the above steps in a continuous cycle to realize the optimization of system performance. In the recent experiment, we applied M-LOOP to train control time sequence for trapping light, repumping light and magnetic field coil current, successfully optimizing OD result from 40 based on traditional compression time sequence to 70 based on machine learning results in ^{85}Rb system, which has realized an OD improvement of nearly 80%.

Furthermore, quantum storage is highly sensitive to environmental inhomogeneous broadening noise, such as atomic thermal motion and magnetic field, which limits the atomic coherence lifetime.[3][4] To overcome this limitation, our future research aims to apply the machine learning method in automation to offset environmental magnetic field noise as much as possible so that we can extend the storage time based on cold atomic ensembles.

References

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