A Photonic Smart Sensor Based on Quantum Memories and Machine Learning

M. Ghadimi[1], **R. Marshman**[1], **G. Milburn**[1], **S. Sharpnel**[1]

1. The University of Queensland, St Lucia, QLD, Australia

email: m.ghadimi@uq.edu.au

Traditional sensors operate in a linear response regime, where changes in signal amplitude are directly proportional to variations in system parameters. However, with the advent of machine learning, sensors can now operate in the non-linear regime [1, 2], leading to the development of "smart sensors". These sensors leverage supervised machine learning methods and labeled data to model the non-linear response of the system to parameter changes. Consequently, they can estimate unknown parameter variations in future experiments.

In our work, we specifically consider an optically probed optomechanical environment, for example, a scenario where a cantilever's mechanical oscillation frequency varies depending on the presence and quantity of impurities in the surrounding air. To capture data, we encode information in the time domain using single-photon pulses. We model this setup as a single-sided optical cavity with a highly reflective output mirror. The reflected pulse's temporal shape, determined by the cavity response function and two parameters (cavity linewidth and detuning), can be used to label the output temporal mode shape.

Our focus is on input pulses prepared with known temporal shapes using Raman schemes [3]. Single photon pulses offer advantages such as enhanced sensitivity to thermal noise compared to coherent pulses with the same average intensity [4]. Additionally, they enable low-power operation, which is highly desirable in biological imaging applications.

To learn the cavity parameters, we drive the cavity with a sequence of identical single-photon pulses and store the amplitude and phase of the reflected signal using a Raman single-photon detector. This data constitutes the nonlinear sensing signal and serves as the training data. By labeling the data with different values of a particular parameter (e.g., mechanical frequency) while holding other parameters constant, a machine learning algorithm can effectively classify the training data based on its dependence on that specific parameter.

In this learning process, a Raman detector utilizes a classical control pulse called the "read" pulse to modify the temporal mode it responds to. By adjusting the read pulse's temporal shape at the Raman detector, the probability of detection can be optimized, minimizing errors. This allows for the implementation of a learning protocol, enabling the sensor to learn the transformation implemented by a single-sided optomechanical cavity. The read pulses are classical and can be modulated using standard techniques, making the approach practical and applicable in various scenarios.

References

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