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Quantum Signal Processing Interferometry: Detecting Rare Events at the Single-Shot Limit

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Quantum sensing leverages quantum resources to achieve measurement capabilities beyond what is possible classically [1,2]. While there is great focus on precision parameter estimation, an underexplored application is single-shot binary-decision making, where the task is to decide whether a signal has been detected. This is particularly advantageous when the underlying event is rare. Quantum Signal Processing Interferometry (QSPI) [3] provides a framework for such decision tasks, allowing one to determine whether the displacement signal's magnitude was above or below a given threshold.

Here, we summarise theoretical and experimental progress toward the realisation of single-shot displacement sensing using the QSPI framework. Our experiment [4] uses a spin-oscillator system in a trapped-ion system. The QSPI protocol consists of a sequence of single-qubit rotations and spin-dependent oscillator displacements that transform an incoming signal applied to the oscillator into a spin projective measurement with a binary outcome. We report extension towards phase-insensitive QSPI with tuneable response functions and dynamic ranges.

[1] Vittorio Giovannetti et al., Quantum-Enhanced Measurements: Beating the Standard Quantum Limit. *Science* 306,1330-1336 (2004). DOI:10.1126/science.1104149.

[2] Christian L. Degen et al., Quantum sensing. *Rev. Mod. Phys.* 89, 035002 (2017). DOI:10.1103/RevModPhys.89.035002.

[3] Jasmine Sinanan-Singh et al., Single-shot Quantum Signal Processing Interferometry. *Quantum* 8, 1427 (2024). DOI: 10.22331/q-2024-07-30-1427.

[4] Alistair R. Milne, Construction of a linear ion trap and engineering controlled spin-motional interactions. PhD thesis, The University of Sydney (2021).

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