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Resource efficient multi-time process tomography using superinstruments

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Precise and robust control of sequences of quantum operations is essential for quantum information processing. The present quantum hardware is plagued with correlated noise, i.e., non-Markovian noise. The existing mitigation strategies, which are based on Markovian assumption, are ineffective. Multi-time process tomography aims to provide a complete description of the nature and strength of the environmental memory, which can then be used to develop control strategies. However, it requires performing an informationally complete set of operations at every intermediate intervention, which include non-deterministic operations such as mid-circuit measurement. These are noisy and slow for the present hardware, making the tomography unreliable and impractical beyond a few steps.

In this work, we provide an efficient procedure for complete characterisation of multi-time processes using superinstruments. Superinstruments are generalisation of local operations to correlated operations across time and can be efficiently implemented through interaction with ancillary systems. Remarkably, we show that a minimal-dimensional quantum ancilla (a qubit) and final measurement is enough to implement an informationally complete set of superinstruments for completely characterising multi-time processes with arbitrary dimensions and arbitrary number of intermediate interventions. Our approach eliminates the error accumulation from repeated measurements and feed-forward, and aligns with capabilities on current platforms where mid-circuit readout is either unavailable or fidelity-limited. The resulting protocol enables practical, scalable identification of non-Markovian memory effects with minimal resource overhead.

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