Quantum Optimal Control with Geodesic Pulse Engineering [1]

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Designing multi-qubit quantum logic gates with experimental constraints is an important problem in quantum computing. In this work, we develop a new quantum optimal control algorithm for finding unitary transformations with constraints on the Hamiltonian. The algorithm, geodesic pulse engineering (GEOPE), uses differential programming and geodesics on the Riemannian manifold of SU(n) for n qubits. We demonstrate significant improvements over the widely used gradient-based method, GRAPE, for designing multi-qubit quantum gates. Instead of a local gradient descent, the parameter updates of GEOPE are designed to follow the geodesic to the target unitary as closely as possible. We present numerical results that show that our algorithm converges significantly faster than GRAPE for a range of gates and can find solutions that are not accessible to GRAPE in a reasonable time. The strength of the method is illustrated with varied multi-qubit gates in 2D neutral Rydberg atom arrays.

In the paper, Ref. [1], we describe the algorithm GEOPE in detail. We use GEOPE to find a number of different quantum gates using Rydberg atom Hamiltonians. In Fig. 1, we show the results of designing a 5-qubit QFT, in which the disparity between the success of the GEOPE and GRAPE methods become clear. In every trial, GEOPE quickly converges to a solution. GRAPE, on the other hand, does not find any solutions within 300 algorithmic steps. Although our implementation of these algorithms is probably not optimal, we note that GEOPE finds these solutions in a couple of minutes, while the second-order GRAPE methods took hours to run (both using 16 CPU cores). We were able to find a 6-qubit QFT with GEOPE for 400 piecewise steps, which was well beyond the capabilities of our GRAPE implementation. We show both numerical and analytical results to demonstrate faster convergence to solutions.

References

[1] Dylan Lewis, Roeland Wiersema, Sougato Bose, https://arxiv.org/abs/2508.16029 (2025)

Figures

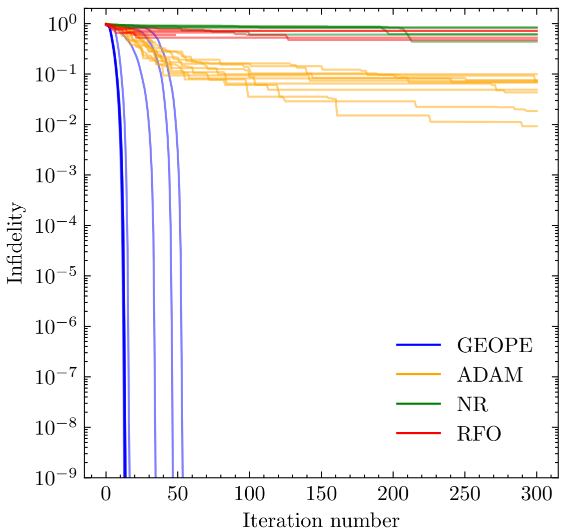

Figure 1: The infidelity of 10 optimisation trials for GEOPE and the GRAPE methods (ADAM, NR, and RFO) is plotted against the algorithmic iteration number. 10 samples for GEOPE and Adam are plotted and 5 samples for the GRAPE methods NR and RFO. The target unitary gate is the 5-qubit QFT gate with 120 piecewise steps (L=120).