Optimizing Robust Quantum Gates in Open Quantum Systems

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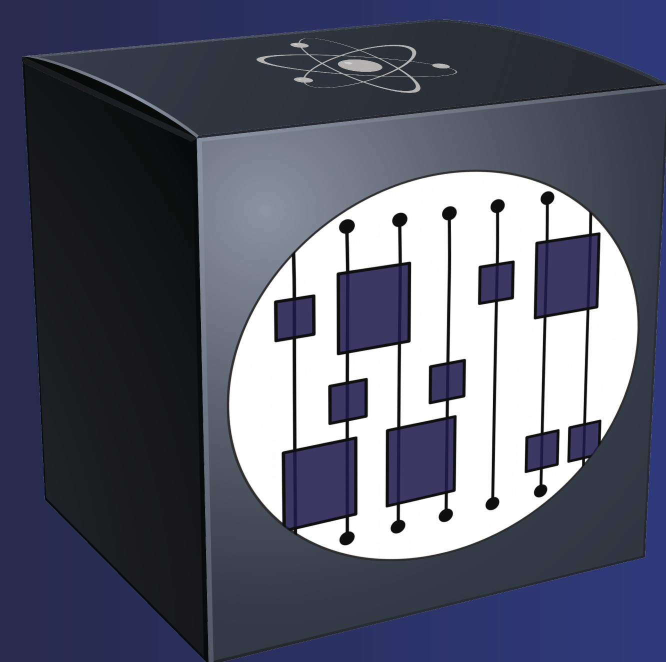

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We are currently at the cusp of a revolution in quantum technology that relies not just on the passive use of quantum effects, but on their active control. At the forefront of this revolution is the implementation of a quantum computer. Encoding information in quantum states as “qubits” allows to use entanglement and quantum superposition to perform calculations that are infeasible on classical computers. The fundamental challenge in the realization of quantum computers is to avoid decoherence – the loss of quantum properties – due to unwanted interaction with the environment. This thesis addresses the problem of implementing entangling two-qubit quantum gates that are robust with respect to both decoherence and classical noise. It covers three aspects: the use of efficient numerical tools for the simulation and optimal control of open and closed quantum systems, the role of advanced optimization functionals in facilitating robustness, and the application of these techniques to two of the leading implementations of quantum computation, trapped atoms and superconducting circuits.

After a review of the theoretical and numerical foundations, the central part of the thesis starts with the idea of using ensemble optimization to achieve robustness with respect to both classical fluctuations in the system parameters, and decoherence. For the example of a controlled phasegate implemented with trapped Rydberg atoms, this approach is demonstrated to yield a gate that is at least one order of magnitude more robust than the best known analytic scheme. Moreover this robustness is maintained even for gate durations significantly shorter than those obtained in the analytic scheme.

Superconducting circuits are a particularly promising architecture for the implementation of a quantum computer. Their flexibility is demonstrated by performing optimizations for both diagonal and non-diagonal quantum gates. In order to achieve robustness with respect to decoherence, it is essential to implement quantum gates in the shortest possible amount of time. This may be facilitated by using an optimization functional that targets an arbitrary perfect entangler, based on a geometric theory of two-qubit gates. For the example of superconducting qubits, it is shown that this approach leads to significantly shorter gate durations, higher fidelities, and faster convergence than the optimization towards specific two-qubit gates.

Performing optimization in Liouville space in order to properly take into account decoherence poses significant numerical challenges, as the dimension scales quadratically compared to Hilbert space. However, it can be shown that for a unitary target, the optimization only requires propagation of at most three states, instead of a full basis of Liouville space. Both for the example of trapped Rydberg atoms, and for superconducting qubits, the successful optimization of quantum gates is demonstrated, at a significantly reduced numerical cost than was previously thought possible. Together, the results of this thesis point towards a comprehensive framework for the optimization of robust quantum gates, paving the way for the future realization of quantum computers.