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(Form 3)

Summary of Doctoral Thesis

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Title Quantum Resource Engineering

Quantum technologies promise unparalleled performance in areas such as field sensing, unstructured database search and integer factorization. In pursuit of these promises, on the design front, schemes for control, communication, and the protection of information have been developed. On the discovery front, a range of disparate physical systems including among others quantum dots, trapped ions, crystal defects, and superconducting circuits, have been investigated for suitability in the machinery of quantum information processing. This process of design and discovery forms the immediate context for the work contained in this thesis. The current era is characterized by severe resource limitations, both in qubit number and in time. These resource limitations will likely continue to play a major role in device design and operation into the foreseeable future, if only due to the sheer magnitude of the costs involved in production and operation. It is therefore in our interest to consider in detail those resources and methods available to us, to engineer greater levels of efficiency. In this two-part thesis I have chosen to focus primarily on aspects relevant to the generation and maintenance of entangled states. These are most relevant in the near-term, in my estimation, to quantum metrology, in the mid-term to (perhaps partially error corrected) quantum communication, and in the long-term to the generation of the fully error corrected states of quantum computation.

In the first part of this thesis I consider general schemes for reducing the impact of local noise for small-scale, near-term quantum devices. I begin with a consideration of the potential role of strong coupling in quantum sensing. The essential feature of this section is the application of strong coupling for passive state protection, a feature well known among researchers interested in passive error mitigation, to quantum sensing. The two key resources of quantum sensing are time and the number of probe systems; by engineering the composite energy level structure of the system, the efficiency of these resources as expressed by quantum sensing's *sensitivity* parameter is enhanced. I conclude that passive protection based on strong coupling overcomes two key limitations of active error correction schemes: Firstly, the pi-pulses of dynamical decoupling commute with the assumed two-qubit interaction terms and the relaxation times of the individual spins improve, not only the coherence time of the system as a whole; secondly, since the probe states are local energy ground states the asymmetric relaxation behavior of the assumed noise process improves the performance, in constrast to active correction methods. I also show a concrete

example, in superconducting flux qubits, where this proposal could be implemented in the near-term to the benefit of relaxation-limited applications in quantum metrology.

Having considered the application of strong coupling to the passive protection of quantum states for sensing, I then begin look at the role of local information in the decoding of the repetition code and the surface code for the protection of quantum states, performing pseudo-threshold simulations using minimum-weight perfect matching and Kolmogorov's *Blossom V* algorithm. The key result of this section is an improvement in resource efficiency when local information is taken into account during the decoding process: My results show that accounting for local variability in measurement errors can reduce logical error rates by factors of order 30%. I also introduce two intuitive but approximate measures of qualitative, predictive utility, and show evidence that this approximate 30% improvement increases for higher code distances and dimensions, under the minimum-weight perfect matching decoder. Finally, an averaged approach to local information for table-lookup and localized decoding schemes based on the geometric mean of local error rates is suggested, and a breakdown of these effects for large-scale systems is predicted.

The second part of this thesis moves down a level in the abstraction hierarchy of quantum technologies to consider the implementation of single-qubit gates, particularly measurement, on two specific physical systems: The nitrogen–vacancy and silicon–vacancy defect centers in diamond. I lead this part with a theoretical performance estimate for an indirect measurement of the electronic spin of the nitrogen–vacancy center based on the reflection statistics of a coupled optical cavity. The scheme investigated here uses dipole-induced transparency to entangle the path of a photon with the spin state of a single nitrogen–vacancy center at cryogenic temperatures. The fidelity of this projective measurement forms the key figure of merit. Incorporating all ground and optically excited states as well as feedback effects in state population across multiple measurement pulses, idealized measurement time and fidelity estimates are provided for current and near-term technology. The impacts of the photon bandwidth on the pulse time and the required cavity decay rate are then incorporated, before providing estimates of the additional error incurred by introducing weak coherent light sources in place of single-photon sources. The central conclusion is that it should be possible to achieve spin measurements with fidelities sufficient for fault tolerant quantum computation. Further, weak coherent light is found to be sufficient for spin measurements for smaller applications such that charge state switching across multiple operations can be considered negligible and when the measurement is not a component of projective entanglement generation.

Having considered the nitrogen-vacancy center, I then move to consider the achievable performance of single-qubit rotations and spin measurements for the negatively charged silicon–vacancy center in diamond. I lead this analysis by justifying a particular field configuration and qubit encoding with respect to the center's energy level structure and decay processes, before providing performance estimates for these operations. Unlike the preceding work for the nitrogen–vacancy center, this section additionally provides and explains performance estimates for optical stimulated Raman adiabatic passage (STIRAP) single-qubit rotations. Results do not exceed expected requirements on operational fidelity for fault tolerant quantum computation, and I therefore conclude with a discussion emphasizing the potential use of silicon–vacancy centers in small-scale or rate-dependent (in contrast to fidelity-dependent) applications.

Finally, the second part of this thesis concludes by outlining potential goals for the near-, mid-, and long-term that may be achieved with a photonic module based on the single, negatively charged nitrogen-vacancy center. These concluding sections explain and provide loose performance estimates for

1. single-node, heralded, memory-assisted quantum communication,
2. distributed quantum sensing, and
3. cluster state generation for quantum computation.

After providing a brief comparison with the silicon–vacancy center considered in the preceding section, I emphasize the suitability of the nitrogen-vacancy center photonic module both for the current resource-limited era and looking further toward scalable quantum information processing.