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Linear Feedback Stabilization for a Continuously Monitored Qubit

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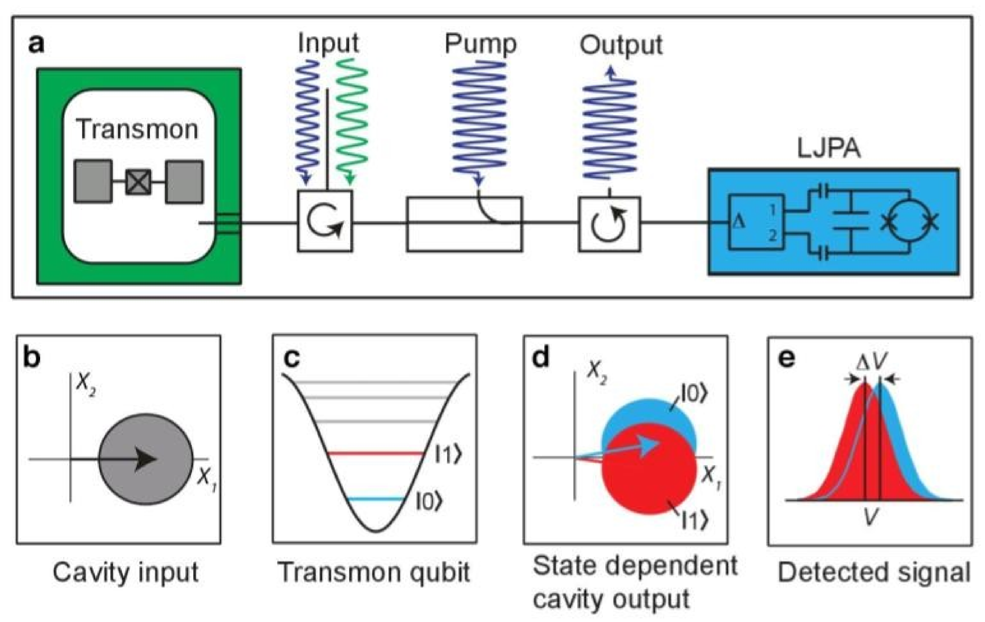
In quantum mechanics, standard or strong measurement approaches generally result in the collapse of an ensemble of wavefunctions into a stochastic mixture of eigenstates while continuous or weak measurements can guide particles into non-trivial superpositions states. These methods are used to control quantum bits or "qubits", the fundamental unit of quantum computers. We explore Hamiltonian driven control through a time-varying Rabi drive by using both analytical derivations of Itô Stochastic Master Equations and numerical simulations.

Experimental Background

Many modern quantum computers consist of one or more superconducting qubits which are created by device known as a Josephson-junction.

A simplified diagram of the computers is offered here, illustrating the quantum wave mechanics and probabilistic features on which these machines are based.



S. J. Weber et al. Nature 511 (2015) doi:10.1038/nature13559

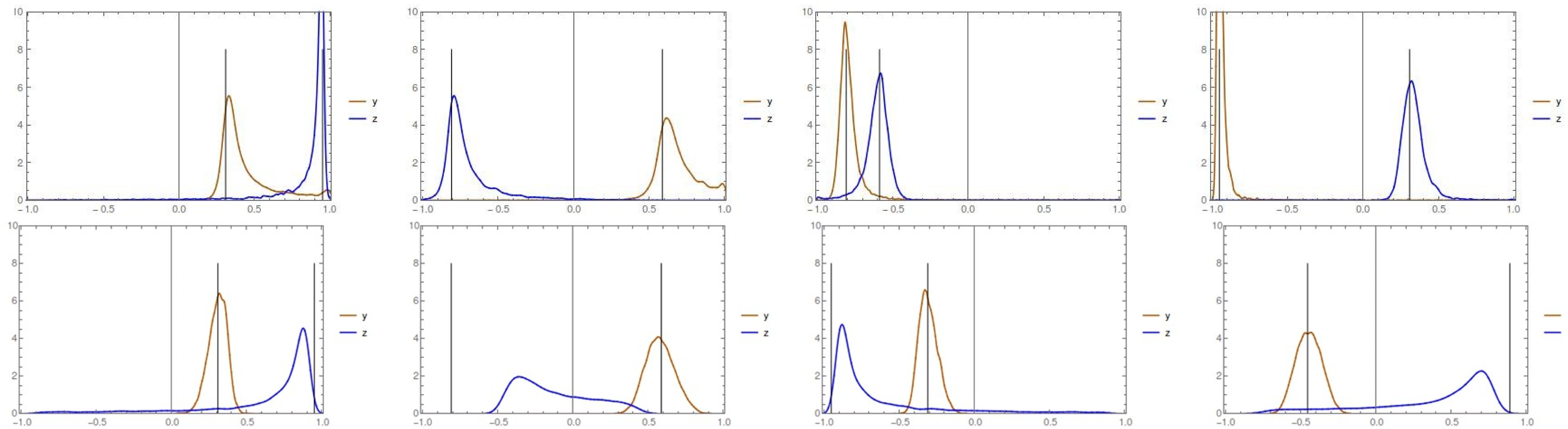
$$\hat{H}(r) = -\Delta(r)\frac{\hat{\sigma}_x}{2}$$

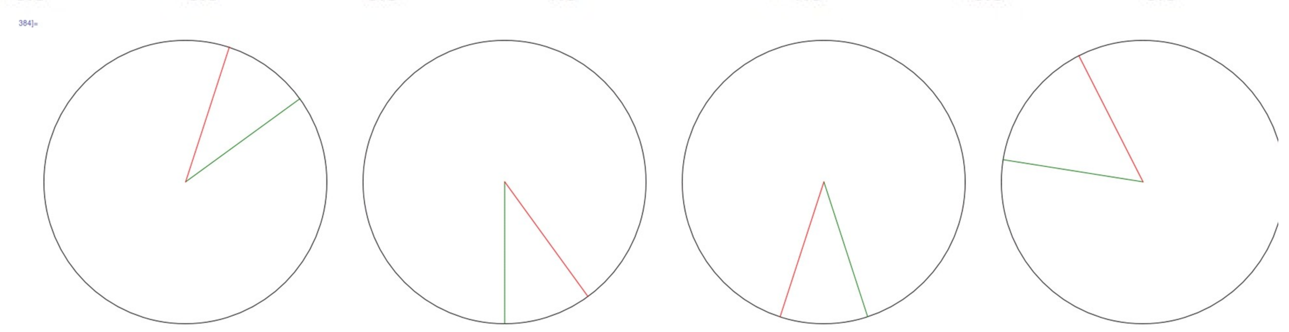
Where $\Delta(r) = \Delta_0 + r\,\Delta_1$

We use Hamiltonian feedback control to stabilize a qubit in a desired state. The signal obtained from continuous measurement is fed back linearly into the driving field of the waveguide in order to control qubit evolution.

Computational Analysis

Below, we see two sets of graphs, the top ideal and the bottom non-ideal (including measurement inefficiency and decoherence). These two sets of graphs show the histogram of both the y and z-components for an ensemble of qubits after trajectories of duration 4T, where T is the average time required for an undriven measurement process to distinguish between two states. Vertical lines are given to show mathematically predicted stabilization points. The short inset below these graphs shows the initial state components (green) and the final state components (red) for these four stabilizations on the qubit Bloch Sphere.





Mathematical Analysis

The density updating function was defined such that it takes into account both measurement (M) and Unitary (U) processes. Our work is on par with current trade standards: measurement duration increment of ten nanoseconds, measurement inefficiency of 0.41, and T1 and T2 decoherence parameters of 60 and 40 microseconds respectively. The analytic equations for both the ideal (upper) and non-ideal (lower) cases are shown below. Non-ideal drive has both y and z formulations.

Ideal drive terms

$$\Delta_0 = -\frac{\cos\theta\sin\theta}{2\tau_m},$$

$$\Delta_1 = \frac{\sin\theta}{\tau_m},$$

Δ_0 - constant drive coefficient
Δ_1 - linear feedback coefficient
θ - Bloch Sphere angle
τ_m - meas. collapse timescale
y_{ss} - final y-component
z_{ss} - final z-component

$\Gamma = 1/2\eta\tau_m + 1/2T_1 + 1/T_2$
$\gamma = 1/T_2$

Non-ideal linear feedback in terms of final y-component and corresponding final z formulation

$$\Delta_1 = \frac{\sqrt{1-2\tau_m y_{ss}(\Gamma y_{ss})}+1}{\tau_m y_{ss}}, \qquad z_{ss} = \frac{\tau_m y_{ss}^2}{-\tau_m y_{ss}^2 + T_1\left(\gamma\tau_m y_{ss}^2 - 1 + a\sqrt{1-2\gamma\tau_m y_{ss}^2}\right)}.$$

Preliminary Conclusions

Ideal non-fixed point stabilization adheres to our analysis. While we have presented local state evolutions, arbitrary relocation on the Bloch Sphere can be achieved through iteration.

The non-ideal case is similar yet more limited. Its stabilization range does not extend in the areas around the equator of the Bloch Sphere, a feature predicted by analysis. While the y-component is in excellent agreement, the z-component exhibits a degree of error.

Z-component error will be reanalyzed. Moreover, the amount of uncertainty in both y and z-components will compared to current trade standards in order to determine the utility of this error correction method in contemporary quantum computers.

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