Quantum Systems: Measurement and Feedback

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Quantum mechanics revolutionized the way physicists describe nature. The laser and the transistor are often advertised as the two main spin-offs of the understanding of quantum mechanical phenomena. However, while quantum mechanics must be used to predict the wavelength of a laser and the operation voltage of a transistor, it does not intervene at the level of the signals processed by these active systems. Signals involve macroscopic collective variables like voltages and currents in a circuit or the amplitude of the oscillating electric field in an electromagnetic cavity resonator. In a true quantum machine, these collective variables which can be controlled and measured and which define the state of the machine, are themselves quantum operators, just as the position of the electron in a hydrogen atom. These machines could allow computers to solve problems inaccessible to classical machines, secure data transmission based on fundamental principles instead of a technological limitation, generate certified random numbers, realize measurements with unprecedented precision, and most likely lead to unforeseen applications in the future.

One of the most needed requirements for operating quantum machines is to prepare various non-classical states with high fidelities, manipulate them reliably and protect them over arbitrary long times. All these requirements lead to the redesign and adaptation of various system theory concepts, such as state and parameter estimation, feedback control, active and passive stabilization, for such physical systems undergoing the laws of quantum physics.

The goal of this mini-course is to present some of the particular features of the quantum systems that one needs to study with extra care while discussing these system theory concepts. Some of the most important features are related to the concept of measurement. While such a measurement is essential for any active stabilizing feedback procedure it introduces modeling complications. We will introduce the concept of measurement back-action for a quantum system and we will show how it can be taken into account in a dynamical model. The back-action being intrinsically a random procedure, such a dynamical model is necessarily a stochastic one. In this regard, we will consider a concrete example based on the frontline experiments by the group of Serge Haroche (2012 physics Nobel prize), Jean-Michel Raimond and Michel Brune at "Ecole Normale Superieure de Paris". This example corresponds to a box in which photons are trapped and are measured by a stream of atoms passing through the box. We will show how a dynamical model can be developed for such a system taking into account various experimental imperfections. We will also study a rather general Lyapunov feedback method that allows stabilizing such a system around its equilibrium states.

In the second part, we will focus on another feature of quantum systems related to the concept of decoherence: the unavoidable coupling to an uncontrolled environment leads to a rapid loss of coherence in quantum information. The short dynamical time-scales imposed by such decoherence phenomena limit, to a great amount, the complexity of the active feedback strategies that could be employed. Indeed, the time-consuming data acquisition and post-treatment of the output signal, lead to an important latency in the feedback procedure. Here, an alternative approach is to apply passive control techniques based on interconnecting the quantum system to be controlled to another strongly dissipative quantum system playing the role of a controller. In this regard, we will focus on another concrete experimental example from the field of circuit quantum electrodynamics. We will illustrate how by coupling a two-level quantum system (qubit) to a damped quantum harmonic oscillator, one can evacuate the entropy and stabilize the ground or the excited state of the qubit.

All the estimation and control techniques that will be explored in this mini-course have been experimented successfully through the past few years.

Outline:

- Two-level quantum system, Quantum harmonic oscillator, composite spin-spring system, Jaynes-Cummings model.
- Discrete-time dynamical models and generalized measurements: hidden Markov chain and Kraus maps, state estimation via quantum filtering and Bayes law.
- Stabilization scheme relying on active measurement-based feedback and control Lyapunov techniques.
- Dissipation and continuous-time Lindblad master equation.
- Stabilization scheme relying on passive reservoir (dissipation) engineering.

The mini-course will be composed of two talks of 50 minutes each.

First talk (Pierre Rouchon): Measurement and state feedback stabilization of quantum systems

Second talk (Mazyar Mirrahimi): Dissipation and passive stabilization of quantum systems

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