Focus on coherent control of complex quantum systems

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Abstract

The rapid growth of quantum information sciences over the past few decades has fueled a corresponding rise in high profile applications in fields such as metrology, sensors, spintronics, and attosecond dynamics, in addition to quantum information processing. Realizing this potential of today’s quantum science and the novel technologies based on this requires a high degree of coherent control of quantum systems. While early efforts in systematizing methods for high fidelity quantum control focused on isolated or closed quantum systems, recent advances in experimental design, measurement and monitoring, have stimulated both need and interest in the control of complex or large scale quantum systems that may also be coupled to an interactive environment or reservoir. This focus issue brings together new theoretical and experimental work addressing the formulation and implementation of quantum control for a broad range of applications in quantum science and technology today.

A systematic theoretical foundation for coherent control of quantum systems began to be developed in the 1980s [1–3], with many formulations adapted from the extensive classical control literature. However, the distinct features of quantum systems have led to a distinct field of coherent quantum control that is characterized by its own characteristic challenges and solutions. The most well known difficulties include the need to maintain coherence and the difficulty of measuring quantum systems, as well as the challenges in scaling up quantum behavior from microscopic to macroscopic scales. Progress is being increasingly made on each of these issues, as experimental advances bring new capabilities to the characterization and manipulation of quantum systems. The papers in this Focus issue describe recent advances in theoretical methodologies of coherent control and applications to physical systems, as well contributions addressing the diverse set of issues raised by control and characterization of the quantum dynamics of large scale quantum systems.

1. Advances in theoretical methodology

Significant progress has been made recently in the monitoring of quantum systems. In particular, the development of fast high fidelity quantum limited measurements for scalable systems such as superconducting qubits has generated renewed interest in systematic development of feedback control for quantum systems. In ‘Global versus local optimality in feedback-controlled qubit purification: new insights from minimizing Renyi entropies’ [4], Teo et al use the relation of minimal Renyi entropies to optimal feedback-controlled qubit purification to elucidate the relationship between local and global optimality of measurement-based feedback protocols. In ‘Rapid steady-state convergence for quantum systems using time-delayed feedback control’ [5], Grimsmo et al explore the use of time-delayed feedback in coherent feedback control without measurement and show that this may be used to speed-up the establishment of steady states. Vuglar and Amini address the general issue of a coherent monitoring of a quantum system in ‘Design of coherent quantum observers for linear quantum systems’ [6], making proposals for design of quantum observers to replace classical measurement-based monitoring. Gough et al address the problem of monitoring continuous matrix product states relevant to non-classical photon fields in ‘Quantum trajectories for a class of continuous matrix product input states’ [7].

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using input-output theory within the SLH formalism to derive the measurement-conditioned quantum master equation and quantum trajectory equations, with application to continuous-mode photonic states.

Control of decoherence and dissipation continues to be a major motivating goal for both theory and experiment. In ‘Optimal control theory for a unitary operation under dissipative evolution’ [8], Goerz et al show how optimal control theory, a well-developed tool for open loop control of isolated quantum systems can be extended to unitary operations under dissipative evolution, adding an important capability to the growing literature on control of open quantum systems. In ‘Arbitrary quantum control of qubits in the presence of universal noise’ [9], Green et al focus on characterization of errors in dynamics of qubits under arbitrary unitary controls in the presence of decoherence, formulating generalized filter functions that allow efficient benchmarking of open loop protocols for noise suppression.

Reflecting an increasing focus in the community on analysis of resources as qubit architectures are scaled to larger sizes and greater complexity, Kallush et al explore the tradeoff between complexity of the control Hamiltonians and sensitivity of the system to noise in the controls in ‘Quantum control with noisy fields: computational complexity versus sensitivity to noise’ [10]. The complexity of control procedures is an emerging theme that is significant for analysis of scaleup of qubit architectures for quantum information. In ‘Reduced coupling with global pulses in quantum registers’ [11], Yuan et al show that the complexity of dynamical decoupling schemes can be significantly reduced by the use of global control pulses. In related work with an emphasis on reaction mechanisms for molecular fragmentation, Xing et al show in ‘Assessment of optimal control mechanism complexity by experimental landscape Hessian analysis: fragmentation of CH2BrI’ [12] how to analyze and minimize the complexity of an optimal control procedure by landscape Hessian analysis, thereby gaining additional insight into the control mechanism.

One of the earliest schemes for quantum information processing is known as adiabatic quantum computing. It requires a slow change of a time-dependent control to interpolate between an initial and final Hamiltonian. Today, adiabatic quantum computation is of particular relevance to current efforts to build experimental prototypes of scalable quantum computers. Several contributions address the issues of error suppression in this computational paradigm. Brif et al use quantum optimal control theory in ‘Exploring adiabatic quantum trajectories via optimal control’ [13] to numerically search for controls that achieve the target final state with a high fidelity while simultaneously maximizing the degree of adiabaticity. In ‘Partial suppression of non-adiabatic transitions’ [14], Opatrný and Molmer focus on errors in the closed system dynamics, introducing a compensating control Hamiltonian to suppress non-adiabatic transitions. In ‘Error suppression and error correction in adiabatic quantum computation: non-equilibrium dynamics’ [15], Sarovar and Young derive a general model for the open quantum system dynamics of an encoded adiabatic quantum computation and analyze the role of non-equilibrium dynamics in error suppression and correction.

The field of pulse design for open loop control is already quite mature and two contributions in this area focus on high-level improvements and applications of pulse sequences. Braun and Glaser develop a systematic approach to development of cooperative composite pulses giving high performance single scan fidelities and relatively short duration in ‘Concurrently optimized cooperative pulses in robust quantum control: application to broadband Ramsey-type pulse sequence elements’ [16]. Bookatz et al present a general Eulerian scheme for undertaking quantum simulation using bounded-strength controls in ‘Hamiltonian quantum simulation with bounded-strength controls’ [17].

2. Implementations, i.e., applications to physical systems

Quantum technology is entering an engineering paradigm with an emphasis on systems design and control. The ability to engineer macroscopic systems, such as superconducting circuits and mechanical resonators, to exhibit coherent quantum behavior is only possible given the ability to control the relevant collective degrees of freedom. While quantized collective degrees of freedom, such as the phase across a Josephson junction, largely factor out of the fundamental quantum degrees of freedom, these interactions remain as a source of dissipation, noise and decoherence. The ability to make these systems behave in a coherent quantum manner requires that we actively control these residual irreversible interactions. The ultimate goal of coherent quantum control of complex quantum systems is quantum computing. Here the difficulty is maintaining coherence in the presence of unknown or uncontrollable interactions with external degrees of freedom.

Many of the required control techniques were developed in the context of condensed matter, atomic/molecular physics and quantum optics but these are now being extended to quite complex engineered systems.

In ‘Scattering of coherent pulses on a two-level system—single-photon generation’ [18], Lindkvist and Johansson show how standard quantum optics methods can be used to describe microwave photon generation in superconducting quantum circuits. They propose using artificial two-level-systems based on Josephson
junctions coupled to two transmission lines to give a very efficient source of on-demand single photon in the microwave spectrum.

Also in the context of superconducting quantum circuits and inspired by the development of Josephson parametric amplifiers in this field, Mirrahimi et al. show in ‘Dynamically protected cat-qubits: a new paradigm for universal quantum computation’ [19] how ideas for processing quantum information using coherent oscillator states, first developed in quantum optics, can be made robust to single-photon loss using continuous photon number parity measurements.

The Jaynes-Cummings model has been central to the study of coherent atomic physics for many decades. In ‘Controlling several atoms in a cavity’ [20], Keyl et al. show that, by tuning coupling constants appropriately, every unitary of the coupled system (atoms and cavity) can be approximated with arbitrarily small error.

Quantum coherent control of trapped ions is one of the primary technology platforms for quantum information processing. In one implementation ions need to be moved around in an entirely coherent fashion i.e., without heating. In ‘Controlling the transport of an ion: classical and quantum mechanical solutions’ [21], Fürst et al. investigate the performance of different control techniques for ion transport in state-of-the-art segmented miniaturized ion traps and show that accurate shuttling can be performed with operation times below the trap oscillation period.

As mentioned above, one of the critical problems for experimental quantum information processing is mitigating the effects of weak interactions with uncontrollable degrees of freedom that lead to noise and decoherence. In ‘Control of open quantum systems: case study of the central spin model’ [22], Arenz et al. consider how to implement gates on a single spin even though it is interacting with many bath spins. Such interactions would normally lead to noise and loss of fidelity for qubit gates but Arenz et al. suggest that sometimes noise can be effectively suppressed through control. In ‘Optimized dynamical control of state transfer through noisy spin chains’ [23], Zwick et al. propose a method of optimally controlling the speed and fidelity of state transfer for a similar model of interacting spins in a chain. Another way to control the effects of noise is to try to control the interaction between the bath degrees of freedom and the system. Various schemes, known generically as decoupling, have been proposed for this. Yuan et al. show in ‘Reduced coupling with global pulses in quantum registers’ [11], that global pulses (reducing the complexity of the controls, as noted above) can be used to reduce the strength of other types of coupling, demonstrating this for Ising couplings. Molecular physics has long been an active domain for the application of quantum control largely due to the technology of pulsed laser sources. In ‘Cooling molecular vibrations with shaped laser pulses: optimal control theory exploiting the timescale separation between coherent excitation and spontaneous emission’ [24], Reich and Koch show how shaping the optical pulses in the optical pumping can be used to implement an optimal control protocol to perform laser cooling of molecules even if the Franck-Condon effects are unfavorable. Kivel et al. demonstrate in ‘Strong-field control of the dissociative ionization of N₂O with near-single-cycle pulses’ [25] how very short pulses (few femtoseconds) can drive and steer molecular reactions taking place on longer time scales by considering the dissociation of N₂O molecules and that the laser creates oriented samples of molecular ions which undergo dissociation.

The experimental demonstration of coherent energy transport in large biomolecular complexes associated with light harvesting has led to the realization that coupling of electronic and vibrational motion can be beneficial rather than deleterious for coherent transport. In ‘Realistic and verifiable coherent control of excitonic states in a light-harvesting complex’ [26], Hoyer et al. provide first indications that coherent control of these complex biological quantum systems can be achieved and verified using ultrafast spectroscopy.

A very different setting for coherent control of molecular systems is presented by Herrera et al. in ‘Infrared-dressed entanglement of cold open-shell polar molecules for universal matchgate quantum computing’ [27]. Here the focus is quantum information processing using polar molecules in optical lattices. They show how quantum gates can be implemented by controlling the interaction between molecules using infrared lasers. The scheme is shown to be robust as a function of the driving parameters.

3. Control and characterization of quantum dynamics of large scale systems

The experimental challenge of coherent quantum processing for many body systems is challenging due to the exponential growth of the tensor product Hilbert space dimension. Developing verification schemes when very large entangled states are involved is difficult. One approach that does not require complex coherent time dependent control is based on adiabatic variation of a Hamiltonian. In ‘Max 2-SAT with up to 108 qubits’ [28], Santra et al. study the performance of a programmable quantum annealing processor, the D-Wave One (DW1) with up to 108 qubits, on the maximum SAT problem with 2 variables per clause (MAX 2-SAT). Another approach that avoids time dependent control is based on the encoding information into topological phases that
are naturally robust to local perturbations. In 'Detecting topological entanglement entropy in a lattice of quantum harmonic oscillators' [29], Demarie et al describe a continuous variable analog of a topologically ordered surface code encoded in harmonic oscillators that is accessible to characterization by quadrature measurements of the oscillators, and analyze its robustness to thermalization and noise in the input states.

Parameter estimation is an important problem for system identification metrology. The parameters could be the values of control fields in a Hamiltonian or the values of some unknown external effect, the size of which we seek to estimate. In a quantum system there have been many proposals to do better than classical schemes by exploiting quantum entanglement and coherent control of quantum states. In any case one must face the particular issues associated with the limits to measurement accuracy imposed by quantum mechanics. In 'Estimation of classical parameters via continuous probing of complementary quantum observables' [30], Negretti and Mølmer consider continuous measurements on an open quantum system and show how the ability to reconstruct the continuous stochastic conditional dynamics using the stochastic Schrödinger equation can be exploited to estimate a parameter in the Hamiltonian, the magnetic field that causes a ground state spin precession in a two-level atom.

Understanding and controlling coherent quantum transport is often an important component of constructing large scale quantum devices. In 'Coherent quantum transport in disordered systems: II. Temperature dependence of carrier diffusion coefficients from the time-dependent wavepacket diffusion method', Zhong et al [31] also use the stochastic Schrödinger equation to investigate carrier transport in one-dimensional systems including both the static and dynamic disorders on site energies. Wang and Cao use a quantum master equation approach in 'Optimal tunneling enhances the quantum photovoltaic effect in double quantum dots' [32] to study the effectiveness of double quantum dots as photovoltaic devices and find that there is an optimal value of interdot tunneling for maximum photovoltaic enhancement. In 'Lattice scars: surviving in an open discrete billiard' [33], Fernandez-Hurtado et al study quantum transport in regular, chaotic, and dissipative billiard systems in which the particles are constrained to lie on lattice sites, finding a class of exceedingly long-lived states in dissipative systems and suggesting ways to realize them physically.

Coherent quantum systems may also be advantageous for resource-efficient implementation of certain classical algorithms. In 'Photonic circuits for iterative decoding of a class of low-density parity-check codes' [34], Pavlichin and Mabuchi show that photonic circuits operated autonomously in the quantum regime provide an efficient and robust ultra-low energy platform for classical signal processing in the low power limit where quantum fluctuations of the optical fields are significant.

The ability to coherently control complex quantum systems with high fidelity is an essential component of quantum information science and technology. This collection of articles shows that our ability to achieve this coherent control is rapidly evolving in response to advances in realization of quantum devices and quantum information processing. The approaches described in this focus issue show excellent promise for further advances in robustness, efficiency, and complexity of control for quantum degrees of freedom in a broad range of environments. The field of coherent control has an important and exciting future as it increasingly factors into design and engineering of complex quantum systems.

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