QI 13: Quantum Control

Time: Wednesday 15:00–18:00 Location: BEY/0245

QI 13.1 Wed 15:00 BEY/0245

A Statistical-Physics Approach to Quantum Control Landscape Exploration — •Malte Krug and Jürgen Stockburger — Institute for Complex Quantum Systems, Ulm, Germany

Conventional approaches to quantum optimal control rely on local optimizers that return a single high-fidelity pulse but offer little insight into the global structure of the cost landscape. A new method is presented, motivated by a statistical-physics inspired approach to stochastic control theory [1], that maps the quantum optimal control problem to an exploration of a high-dimensional landscape using ideas from protein-folding methods [2]. Instead of a single pulse, the method generates a distribution of control trajectories, represented by a Markov chain whose stationary distribution reflects the dominant regions of the cost landscape. This ensemble captures globally competitive pulses, reveals the diversity of near-optimal solutions, and allows for characterization of the local landscape through soft and stiff directions around optimal pulses. Moreover, the sampled trajectories provide high-quality initial guesses for conventional optimization methods, strongly biased toward the most promising regions of the landscape.

[1] Kappen, H. J.,*Phys. Rev. Lett.* 95, 200201 (2005).
[2] Trebst, S. & Troyer, M., in: *Computer Simulations in Condensed Matter Systems*, eds. Ferrario, M., Ciccotti, G. & Binder, K., Springer (2006).

QI 13.2 Wed 15:15 BEY/0245

Closed-Loop Control with Tailored Benchmarking Protocols — •Matthias Müller — Forschungszentrum Jülich

Quantum technology is a fast-emerging field with both scientific and technological importance. The performance relies on unique features like superposition and entanglement and depends on sophisticated mechanisms of control to perform the desired tasks. Quantum Optimal Control (QOC) has proven to be a powerful tool to accomplish this task. I will give a brief overview on the CRAB algorithm for QOC [1] and the optimal-control software QuOCS [2], and then talk about recent work on closed-loop control [3,4,5] for one- and two-qubit gates.

[1] M. M. Müller et al., Rep. Prog. Phys. 85 076001 (2022) [2] M. Rossignolo et al. Comp. Phys. Comm. 291, 108782 (2023) [3] N. Oshnik et al., Phys. Rev. A 106, 013107 (2022) [4] P. Vetter et al., npj Quantum Information 10 (1), 96 (2024) [5] A. Marcomini et al., in preparation (2025)

QI 13.3 Wed 15:30 BEY/0245

Efficient pulse-sequence optimization method for quantum control under realistic hardware constraints — Marco Dall'Ara[1,2], Florentin Reiter[1], Thomas Wellens[1], Martin Koppenhöfer[1], and •Walter Hahn[1] — [1]Fraunhofer Institute for Applied Solid State Physics IAF, Freiburg, Germany — [2]Dipartimento di Fisica e Astronomia G. Galilei & Padua Quantum Technologies Research Center, Università degli Studi di Padova, Padova, Italy

We propose a simple yet efficient pulse-sequence optimization method for controlling quantum systems. The ansatz leads to an efficient exploration of the unitary space without over-parameterization, even when the pulse amplitudes are restricted to a few discrete values suitable for quantum devices. Bandwidth and power limitations of experimental settings can be straightforwardly included with only minor computational overhead. We numerically validate the method by applying it to (i) unitary synthesis of a three-qubit gate and (ii) ground-state preparation on a globally-driven Rydberg-atom platform, and (iii) state transfer in an Ising spin chain. For all problems considered, our method approaches an information-theoretic lower bound on the number of parameters and exhibits advantages when compared to commonly used quantum control algorithms.

QI 13.4 Wed 15:45 BEY/0245

Optimal Control for Open Quantum System in Circuit Quantum Electrodynamics — •Francisco Cardenas-Lopez[1] and Xi Chen[2] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany — [2]Instituto de Ciencia de Materiales de Madrid (CSIC), Cantoblanco, E-28049 Madrid, Spain

We propose a quantum optimal control framework based on the Pontryagin Maximum Principle to design energy- and time-efficient pulses for open quantum systems. By formulating the Langevin equation of a dissipative LC circuit as a linear control problem, we derive optimized pulses with exponential scaling in energy cost, outperforming conventional shortcut-to-adiabaticity methods such as counter-diabatic driving. When applied to a resonator dispersively coupled to a qubit, these optimized pulses achieve an excellent signal-to-noise ratio comparable to longitudinal coupling schemes across varying critical photon numbers. Our results provide a significant step toward efficient control in dissipative open systems and improved qubit readout in circuit quantum electrodynamics.

QI 13.5 Wed 16:00 BEY/0245

Learning to Steer Quantum Mmany-Body Dynamics with Tree Optimization — Jixing Zhang[1], Bo Peng[2], Yang Wang[1], •Cheuk Kit Cheung[1], Guodong Bian[3], Andrew Edmonds[4], Matthew Markham[4], Zhe Zhao[2], Durga Dasari[1], Ruoming Peng[1], Ye Wei[2], and Jörg Wrachtrup[1] — [1]3rd Institute of Physics, University of Stuttgart, Allmandring 13, Stuttgart, 70569, Germany — [2]Department of Data Science, City University of Hong Kong, Hong Kong, China — [3]School of Chemistry, University of Birmingham, B15 2TT, Edgbaston Birmingham, UK — [4]Element Six Global Innovation Centre, Fermi Avenue, Harwell Oxford, Didcot, Oxfordshire OX11 0QR, United Kingdom

Achieving practical quantum technologies requires high-quality control over complex quantum systems, but progress is hindered by exponentially growing state spaces and experimental challenges. We present an AI framework that learns to design optimized pulse sequences for many-body spin control, offering a powerful alternative to conventional theory-driven methods. The framework combines tree search, neural network filtering, and numerical simulation guidance to navigate highly nonlinear optimization landscapes using minimal resources. It identifies high-performing, non-intuitive sequences that established methods struggle to find. Experiments in a diamond spin ensemble show the best AI-designed sequences achieved spin coherence times exceeding 200 microseconds, a 100% improvement over state-of-the-art baselines. This work highlights AI's potential to steer complex many-body dynamics, marking a decisive shift toward data-driven sequence design.

QI 13.6 Wed 16:15 BEY/0245

Efficient analytical gradient evaluation for locally-interacting large multi-qubit platforms — •Alessandro Ciani[1], Ashutosh Mishra[1,2], Elena Lupo[1], and Frank Wilhelm-Mauch[1,2] — [1]Forschungszentrum Jülich, Jülich, Germany — [2]Universität des Saarlandes, Saarbrücken, Germany

We present a general framework for the computation of derivatives of time-ordered propagators in quantum optimal control, for both closed and open quantum systems, with respect to any general pulse parameterization, by deriving the formal solution from first principles. We obtain a series expansion for the gradients of the propagator, and utilize locality constraints to efficiently compute the derivatives. Further, we demonstrate that such a method can be used to efficiently compute gradients in large multi-qubit platforms, without running necessarily into the problem of storing the whole quantum state, whose size grows exponentially with the number of qubits. Our approach, can be viewed in terms of the recently introduced Pauli propagation framework applied to the computation of gradients in optimal control tasks. Finally, we show that our method is capable of accurately estimating the gradients, with much reduced memory and runtime compared to direct numerical evaluation.

30min. break

QI 13.7 Wed 17:00 BEY/0245

Analytical flux-tuned iSWAP pulse suppressing leakage channels — •Dimitrios Georgiadis[1,2], Boxi Li[1], Francisco Cardenas Lopez[1], and Felix Motzoi[1,2] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, Zülpicher Straße 77, 50937 Cologne, Germany

Achieving fast, high-fidelity qubit gates remains one of the major challenges in quantum computing, and despite recent progress, enhancing the efficiency of superconducting two-qubit gates still presents complications. In this work we investigate optimal control methods in order to improve the fidelity of two qubit gates in a flux tunable architecture based on a tunable coupler. We emphasize the importance of suppression of various leakage channels and we demonstrate simulations with analytical optimal control methods, (DRAG) and (DRAG-like), on the external flux on the tunable coupler, achieving further improved fidelities for an iSWAP gate. Finally, we propose a generalized pulse-shaping approach for the external flux, leading to significant leakage suppression across different circuit parameters.

QI 13.8 Wed 17:15 BEY/0245

Autonomous reachability of quantum states on random graphs — •Konrad Szymański[1], Tomasz Andrzejewski[2], Yuri Minoguchi[2], and Phila Rembold[2] — [1]Research Center for Quantum Information, Bratislava, Slovakia — [2]Atominstitut, TU Wien, Vienna, Austria

We study a particle hopping on a graph under a Hamiltonian with fixed but tunable couplings (no time-dependent control). We ask: which states can be reached from a given initially localized state via such autonomous dynamics? The Hamiltonian is a linear combination of generators corresponding to graph edges, with weights chosen freely but held constant during evolution. We develop three criteria to determine whether a given state is reachable from another. The first is analytical: if a certain matrix constructed from expectation values of the two states is strictly positive definite, the target state is certified unreachable from the initial one. The remaining two rely on numerical optimization over overlaps in the Hamiltonian eigenspaces and Krylov subspace structure. Applying these tools to random graph ensembles, we characterize how the fraction of Haar-random pure states that are unreachable from a localized initial state depends on graph connectivity.

QI 13.9 Wed 17:30 BEY/0245

Coherent control in V-type system: Simulation insights using intense two-dimensional coherent spectroscopy — •Rishabh Tripathi, Krishna Maurya, and Rohan Singh — Indian Institute of Science Education and Research (IISER) Bhopal, Bhopal, India

Our study investigates coherent control in V-type three-level systems using high-intensity, ultrafast laser pulses, explored through two-dimensional coherent spectroscopy (2DCS). Employing numerical solutions of the optical Bloch equations, we analyze the response of a V-type system to Gaussian pulses of 10 fs and 120 fs. The research reveals that shorter pulses induce uniform Rabi oscillations, whereas longer pulses result in complex quantum interference and state-specific population dynamics. This distinction underscores the pivotal role of pulse duration and spectral properties in modulating quantum interactions. Our 2DCS simulations, utilizing phase-cycling methods, provide insight into the system's spectral response in both perturbative and non-perturbative regimes. These simulations reveal the manipulation of spectral peak amplitudes and phases by adjusting the pulse areas, demonstrating control over the system.

This work contributes to the understanding of light-matter interactions in quantum systems and highlights the potential of tailored laser pulses for advanced coherent control, with implications for atomic vapors, semiconductor nanostructures, and photonics research.

QI 13.10 Wed 17:45 BEY/0245

Applications of dynamical decoupling to qubit noise suppression — •Chun Kit Dennis Law[1], Francisco Andrés Cárdenas-López[2], and Felix Motzoi[3] — [1]Peter Grünberg Institute, Forschungszentrum Jülich, Institute of Quantum Control (PGI-8), D-52425 Jülich, Germany — [2]Peter Grünberg Institute, Forschungszentrum Jülich, Institute of Quantum Control (PGI-8), D-52425 Jülich, Germany — [3]Peter Grünberg Institute, Forschungszentrum Jülich, Institute of Quantum Control (PGI-8), D-52425 Jülich, Germany

Noises are one of the major sources of the high error rates in the operation of modern quantum devices. Dynamical decoupling are some of the earliest experimentally demonstrated and least resource-intensive methods to suppress errors. We construct a many-level quantum system and isolate the lowest two energy levels for information processing. Upon the introduction of noise, we investigate how effective the XY4 sequence is by studying the associated leakage and the fidelity concerning the lowest two energy levels. Time permitting, we also investigate the effects of modifying the pulse shape by DRAG (derivative removal by adiabatic gate), which has been successfully applied to superconducting qubits to reduce leakage and phase errors.