QI 23: Quantum Control

Time: Thursday 9:30–13:00 Location: HFT-FT 131

QI 23.1 Thu 9:30 HFT-FT 131

Neural-network-supported preparation of cat states in Jaynes-Cummings model — •Pavlo Bilous[1], Hector Hutin[2], Benjamin Huard[2], and Florian Marquardt[1,3] — [1]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany — [2]Ecole Normale Supérieure de Lyon, CNRS, Laboratoire de Physique, 69342 Lyon, France — [3]Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

We present a neural-network (NN) based approach for control optimization in the Jaynes-Cummings model allowing for high-fidelity preparation of cat states $\psi_{\mathrm{cat}}(\alpha)$ in the cavity. The NN is first trained on a random selection of α-values sampled from a region of interest and can be afterwards applied to *any* α from this region for construction of the $\psi_{\mathrm{cat}}(\alpha)$ state. The data processing pipeline consisting of the NN and a Schrödinger equation solver ensures the construction of the proper fields driving the qubit and the cavity at the training stage. For each training point α, the controls are optimized to minimize the loss function defined as the infidelity of the resulting state $\psi(\alpha)$ with respect to the target state $\psi_{\mathrm{cat}}(\alpha)$. We search for the control fields as an expansion in a so called B-spline basis used extensively in computational atomic physics. This approach reduces significantly the number of parameters needed to characterize the driving signals and ensures their well-behaved shape feasible for experimental implementation. We generalize our approach for the construction of other quantum states described by one or a few parameters.

QI 23.2 Thu 9:45 HFT-FT 131

Modelling two-qubit gates of superconducting transmon processors — Michael Krebsbach, •Martin Koppenhöfer, and Thomas Wellens — Fraunhofer-Institut für Angewandte Festkörperphysik IAF, Tullastraße 72, 79108 Freiburg, Deutschland

Two-qubit gate errors remain one of the biggest obstacles on the road towards scalable quantum processors and circuits. In fixed-coupling superconducting transmon qubits, crosstalk effects can cause a significant degradation of two-qubit gate fidelities [1]. A precise understanding of these errors and their origin is an important step for error mitigation and thus crucial for the implementation of deeper circuits. We develop a noise model based on Hamiltonian simulation of coupled three-level systems, taking into account higher transmon levels and their anharmonicities. By comparing simulation results with experiments on IBM hardware, we identify important error mechanisms such as frequency collisions and investigate their impact on gate fidelities. [1] A. Ketterer and T. Wellens, Phys. Rev. Applied 20, 034065 (2023)

QI 23.3 Thu 10:00 HFT-FT 131

Qunatum Information Storage in Cavity Coupled Spin Ensembles — •Michael Schilling and Jószef Zsolt Bernád — Forschungszentrum Jülich, Jülich, Deutschland

Recent investigations have highlighted the potential of spin ensembles coupled to a cavity as a robust platform for quantum information storage, demonstrating remarkable coherence times of 500ms. A primary challenge in this context is the efficient absorption of photons by the spin ensemble from external sources. We have developed a semi-analytical framework to significantly enhance this absorption process, achieving an 1.7-fold speedup compared to existing methodologies. Additionally, to maintain the integrity of quantum information stored within the ensemble, we optimize quantum operations, facilitating the implementation of dynamical decoupling sequences. To this end we expanded upon the Hierarchical Equations of Motion (HEOM) method, enabling its application to quasi-continuous distributions of spins.

QI 23.4 Thu 10:15 HFT-FT 131

Quantum Circuits Noise Tailoring from a Geometric Perspective — •Junkai Zeng[1,2], Yong-Ju Hai[2], Hao Liang[1,2], and Xiu-Hao Deng[1,2] — [1]Shenzhen Institute for Quantum Science and Engineering (SIQSE), Southern University of Science and Technology, Shenzhen, P. R. China — [2]nternational Quantum Academy (SIQA), and Shenzhen Branch, Hefei National Laboratory, Futian District, Shenzhen, P. R. China

Quantum errors resulting from unwanted interactions with noisy environments pose a significant challenge to the advancement of quantum information technology. It is well known that quantum gates can resist noise by optimizing control pulse waveforms. On the other hand, despite using noisy individual gate operations, high-fidelity quantum circuit output can still be achieved through optimized, noise-aware circuit compilation. We show that a recently developed geometric tool for controlling and analyzing continuous noisy qubit dynamics, termed Quantum Erroneous Evolution Diagram (QEED), can be extended to study quantum errors at the circuit level. We show how introducing twirling operations can create equivalent quantum circuits with altered evolution diagrams that exhibit reduced error, and randomized compiling is essentially analogous to averaging over an ensemble of random walk trajectories from this viewpoint. We further show how combining randomized compiling with robust quantum control at the gate level can significantly enhance circuit fidelity.

QI 23.5 Thu 10:30 HFT-FT 131

Universal readout error mitigation — •Adrian S. Aasen[1,2], Andras Di Giovanni[3], Hannes Rotzinger[3,4], Alexey V. Ustinov[3,4], and Martin Gärttner[1,2] — [1]Kirchhoff-Institut für Physik, Universität Heidelberg, Heidelberg, Germany — [2]Institut für Festkörpertheorie und -optik, Friedrich-Schiller-Universität Jena, Jena, Germany — [3]Physikalisches Institut, Karlsruher Institut für Technologie, Karlsruhe, Germany — [4]Institut für QuantenMaterialien und Technologien, Karlsruher Institut für Technologie, Karlsruhe, Germany

Quantum technologies rely heavily on accurate control and reliable readout of quantum systems. Current experiments are limited by numerous sources of noise that can only be partially captured by simple analytical models and additional characterization of the noise sources is required. To overcome this challenge, we designed a universal readout error mitigation protocol. This protocol is based on quantum state tomography (QST), which estimates the density matrix of a quantum system, and quantum detector tomography (QDT), which characterizes the measurement procedure. By treating readout error mitigation in the context of state tomography the method becomes largely device-, architecture-, noise source-, and quantum state-independent.

QI 23.6 Thu 10:45 HFT-FT 131

Benchmarking a readout noise mitigation method on a superconducting qubit — •Andras Di Giovanni[1], Adrian S. Aasen[3,4], Hannes Rotzinger[1,2], Martin Gärttner[3,4], and Alexey V. Ustinov[1,2] — [1]Physikalisches Institut, — [2]Institut für QuantenMaterialien und Technologien, Karlsruher Institut für Technologie, Karlsruhe, Germany — [3]Kirchhoff-Institut für Physik, Universität Heidelberg, Heidelberg, German — [4]Institut für Festkörpertheorie und -optik, Friedrich-Schiller-Universität, Jena, Germany

Quantum technologies rely both on precise control and accurate readout of quantum systems. Current experiments are limited by numerous sources of noise that can only be partially captured by analytical models and therefore additional characterization of the noise sources is required. We benchmark a device tomography based method for readout error mitigation on a superconducting qubit. For this, we implement an experiment on a transmon with the goal of increasing its readout fidelity. In this talk, we present experimental results obtained by characterizing the performance of the method by carrying out a systematic sweep of noise sources on a superconducting qubit chip: suboptimal readout signal amplification and resonator photon population, off-resonant qubit drive, and effectively increased decoherence. Overall, a significant improvement of the infidelity up to a factor of 30 is observed, enabling the reliable readout of very noisy quantum systems.

15 min. break

QI 23.7 Thu 11:15 HFT-FT 131

Quantum gate design with machine learning — •Bijita Sarma and Michael Hartmann — Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), Erlangen, 91058, Germany

Designing of fast and high fidelity quantum gates is crucial for getting the most out of current quantum hardware since detrimental effects of decoherence can in this way be minimised during the operation of the gates. However, achieving fast gates with high-fidelity and desirable efficiency on the state-of-the-art physical hardware platforms remains a formidable task owing to the presence of hardware level errors and crosstalk. In recent years, machine learning (ML)-based methods have found widespread applications in different domains of science and technology for nontrivial tasks. In this work, we exploit the power of ML to design quantum gates that uses the hardware-level leakage errors to one's advantage. These gates are found to exhibit controlled leakage dynamics in and out of the computational states at appropriate times during the course of the gate that makes these extremely fast.

QI 23.8 Thu 11:30 HFT-FT 131

Robust quantum gates for dynamical correction of coherent errors — •Xiu-Hao Deng[1,2], Yong-Ju Hai[1], Yuanzhen Chen[1,2], and Kangyuan Yi[1] — [1]Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China — [2]Guangdong Provincial Key Laboratory of Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China

In this talk, I will present our theory and experimental results. As quantum circuits become more integrated and complex, additional error sources that were previously insignificant start to emerge. Consequently, the fidelity of quantum gates benchmarked under pristine conditions falls short of predicting their performance in realistic circuits. To overcome this problem, we must evaluate their robustness against pertinent error models beyond isolated fidelity. Here we will report the theory of a geometric framework for diagnosing and correcting various errors and the experimental realization of robust quantum gates in superconducting quantum circuits based on this approach. Using quantum process tomography and randomized benchmarking, we demonstrate robust single-qubit gates against a quasi-static noise in a broad range of strengths, which is a common source of correlated errors. We also apply our method to non-static noises and to realize robust two-qubit gates. Our work provides a versatile toolbox for achieving noise-resilient complex quantum circuits.

QI 23.9 Thu 11:45 HFT-FT 131

Accurate Quantum Feedback Control via Conditional State Tomography with Reinforcement Learning — •Sangkha Borah[1,2] and Bijita Sarma[2] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany — [2]Friedrich-Alexander-Universitat Erlangen-Nurnberg, Staudtstraße 7, 91058 Erlangen, Germany

The efficacy of measurement-based feedback control (MBFC) protocols faces challenges due to the presence of measurement noise, impacting the accurate inference of the underlying dynamics of a quantum system from noisy continuous measurement records. This, in turn, hinders the determination of precise control strategies. To address these limitations, this study investigates a real-time stochastic state estimation approach facilitating noise-free monitoring of conditional dynamics, encompassing the complete density matrix of the quantum system. Referred to as 'conditional state tomography,' this method allows for leveraging noisy measurement records within a single quantum trajectory. Consequently, it empowers the development of refined MBFC strategies, effectively overcoming the constraints posed by measurement noise. The proposed approach holds promise for diverse feedback quantum control scenarios and proves particularly advantageous for reinforcement-learning (RL)-based control. In RL applications, the agent can be trained using arbitrary conditional averages of observables or the full density matrix as input, enabling the rapid and accurate learning of control strategies.

QI 23.10 Thu 12:00 HFT-FT 131

Quantum control landscapes of piecewise-constant pulses — •Martino Calzavara[1,2] and Felix Motzoi[1] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), Jülich 52425, Germany — [2]Institute for Theoretical Physics, Universität zu Köln, Cologne 50937, Germany

Since the introduction of the GRAPE algorithm for the efficient computation of fidelity gradients, piecewise-constant controls have become a widely adopted ansatz for studying Quantum Optimal Control problems.

The time evolution for this class of time-dependent Hamiltonians can be represented through a parametrized quantum circuit, allowing us to analyze the properties of fidelity as a function of the control pulses - the so-called control landscape - by employing concepts and techniques from the fields of Variational Quantum Circuits and Quantum Machine Learning. Among these techniques, Fourier spectrum analysis has proven valuable in gaining insights into the representational power of these quantum circuits.

In this study, we present a Fourier representation of GRAPE landscapes that enables us to numerically and analytically investigate relevant landscape properties. Notably, these properties are found to depend on a non-dimensional parameter that expresses the time-energy budget of the time evolution.

QI 23.11 Thu 12:15 HFT-FT 131

Deciding Observability in Quantum Dynamics Easily — Markus Wiener and •Thomas Schulte-Herbrüggen — Technical University of Munich (TUM)

Among the questions arising in quantum engineering there is a practical yet fundamental one: given a controlled quantum dynamical system, for which observables can measurements give full information for system identification?

In finite-dimensional closed systems, a unified (Lie) frame of quantum systems theory settles this observability problem—as will be illustrated in paradigmatic n-qubit systems. Implications and generalisations will be outlined as well.

QI 23.12 Thu 12:30 HFT-FT 131

Reinforcement learning entangling operations for spin qubits — •Mohammad Abedi — Forschungszentrum Jülich. Germany

Traditional methods of optimising control pulses rely on the ability to compute gradients of a model of the system dynamics. We investigate reinforcement learning (RL) is a model-free alternative, which optimises entangling operations directly from experience by interacting with a quantum dot spin qubit system. While employing a detailed numerical model of the quantum chip at this point, we explore how the realistically limited observation on quantum systems can be augmented via sequential autoregressive learning with transformer models.

QI 23.13 Thu 12:45 HFT-FT 131

Improving robustness of quantum feedback control with reinforcement learning — •Manuel Guatto, Francesco Ticozzi und Gian Antonio Susto — Università degli studi di Padova, 35131 Padova, via Gradenigo 6B

Different reinforcement learning techniques are used to derive a feedback law for state preparation of a target state for a test system undergoing varying amounts of noise that is not included in the system model. Comparing the results indicates that the learned controls are more robust to unmodeled perturbations with respect to simple feedback strategy based on optimized population transfer, and that training on simulated nominal model retain the same advantages displayed by controllers trained on real data. The possibility of effective off-line training of robust controllers promises significant advantages towards practical implementation.