QCE24 WKS 33 (Fri, Sep 20, 2024)

Novel Applications of Optimal Control and Calibration for Quantum Technology

Session I: 10:00-11:30 Eastern Time (EDT) — UTC-4

10:00AM -10:15AM	**Ronan Gautier** Optimizing transmon readout with dynamiqs, a library for GPU-accelerated and differentiable quantum simulations
10:15AM -10:30AM	**Anders Petersson and Stefanie Guenther** Time-parallel multiple-shooting for multi-qubit optimal control
10:30AM -10:45AM	**Daniel Appelö** Kraus is King: High-order Completely Positive and Trace Preserving (CPTP) Low Rank Method for the Lindblad Master Equation
10:45AM -11:00AM	**Aaron Trowbridge** Piccolo.jl: an integrated quantum control & calibration stack in Julia
11:00AM -11:30AM	**Session panel** Ronan Gautier, Anders Petersson, Daniel Appelö, Aaron Trowbridge

Session II: 12:30-14:00 Eastern Time (EDT) — UTC-4

12:30PM -12:45PM	**Élie Genois** Quantum optimal control of superconducting qubits based on machine-learning characterization
12:45PM -1:00PM	**Max Hays** Reinforcement learning for control of superconducting qubits
1:00PM -1:15PM	**Zac Manchester** The Gray Area Between Optimal Control and Reinforcement Learning: Using Data and Models Together for Better Quantum Control
1:15PM -1:30PM	**Murphy Niu** Feedforward and Machine Learning for Quantum Control towards Near-term Applications
1:30PM -2:00PM	**Session panel** Élie Genois, Max Hays, Zac Manchester, Murphy Niu

Session III: 15:00-16:30 Eastern Time (EDT) — UTC-4

3:00PM -3:15PM	**David Kanaar** Designing silicon spin qubit gates robust to charge noise with Hamiltonian decomposition and numerical methods
3:15PM -3:30PM	**Alexandre Bourassa** Calibrating large quantum systems for error correction
3:30PM -3:45PM	**Benjamin Lienhard** Inherent and Engineered Noise-Robustness of Quantum Processors
3:45PM -4:00PM	**Ryan Sitler** Optimally Band-Limited Noise Filtering and Crosstalk Mitigation for Single Gates in Multi-Qubit Systems
4:00PM -4:30PM	**Session panel** David Kanaar, Alexandre Bourassa, Benjamin Lienhard, Ryan Sitler

Workshop summary and abstract

Workshop summary — In the second iteration of this workshop, researchers come together to discuss recent advancements in the optimal control and characterization of quantum devices. With a particular focus on novel applications, attendees will learn about current state-of-the art schemes as well as their challenges and limitations.

Workshop abstract — Recent advances in the design of quantum technologies has led to rapidly increasing numbers of qubits in current quantum computing hardware. However, accurately controlling these large quantum systems remains a fundamental challenge in the current NISQ era and a central task in the successful implementation of quantum-enhanced technologies. Analog control pulses provide the fundamental interface between the quantum compiler and the quantum hardware, and significant progress has been made in the development of computational tools to design control pulses that can realize desired operations with high fidelity. However, the implementation of optimal control techniques on physical quantum devices remains challenging due to numerous obstacles such as model-device discrepancies, high calibration cost, and control hardware limitations. As quantum systems continue to grow in size and complexity, it is essential that we continue to develop and improve optimal control techniques together with modern calibration methods to fully harness their potential. This is the second time the workshop would take place. While in 2023 (WKS05) the focus lay on the design of scalable numerical methods for optimal control and hardware characterization, in this year's iteration special emphasis is placed on applications of optimal control and its interplay with calibration of quantum devices. Researchers from diverse backgrounds will come together to discuss state-of-the-art optimal control methods and their implementation in different quantum technologies. It provides a platform to develop and foster collaborations amongst different research groups, discuss current challenges and potential solutions, and present new methodologies and applications. During a mix of invited talks and discussion panels, theoretical, numerical, and experimental advances will be presented and analyzed.

Speaker, titles, and abstracts

Speaker — Daniel Appelö
Title — Kraus is King: High-order Completely Positive and Trace Preserving (CPTP) Low Rank Method for the Lindblad Master Equation
Abstract — Our goal is to design high order accurate methods for quantum control and characterization of open systems. The methods exploit low rank structure in the density matrix while respecting the essential structures of the Lindblad equation. A defining feature of the Lindblad equation is that its evolution of the density matrix preserves complete positivity (CP) and is trace preserving (TP).

It is known that no explicit Runge-Kutta method is CP. Consequently, considerable effort has been spent on designing numerical schemes that are in Kraus form. A pioneering work in this direction is Steinbach 1995, where a Taylor series expansion technique is used and explicit formulae defining schemes up to fourth order accuracy are provided. Later work by Cao and co-authors are based on various techniques including the use of Duhamel's principle and principles of stochastic unraveling. While these schemes are of interest, we remark that they are single-step, single-stage methods, and the techniques used makes the construction of high order accurate schemes complicated.

Another property of the density matrix that is prominent in many quantum systems, in particular for those with low entropy, is that it can be effectively approximated by low rank techniques. When present, low rank structure can and should be exploited to accelerate simulations and reduce memory footprint. As shown in this paper, the Kraus form plays well with low rank structures and operations can be performed directly on low rank Cholesky factors. In the literature, a standard approach for evolving low rank structures is the time-dependent variational principle (TDVP, Dirac 1930). However, since the tangent projection of the Lindbladian onto the low rank density matrix manifold in general may not be Lindbladian, a numerical scheme with the CP property resulting from TDVP is not possible to the best of the authors' knowledge.

In this talk we show how Choi's theorem provides a way to construct numerical methods that are provably CPTP and can be easily implemented in low rank form.

Speaker — Alexandre Bourassa
Title — Calibrating large quantum systems for error correction
Abstract — Flagship quantum systems have been steadily growing over the years leading to ever larger quantum circuit demonstrations. Continued scaling of these demonstrations is dependent on our ability to build both component and circuit level calibrations that are fast, reliable, and automated. In this talk, we will explore different calibration strategies and techniques used on Google’s state-of-the-art quantum hardware in the context of achieving our quantum error correction goals.

Speaker — Ronan Gautier
Title — Optimizing transmon readout with dynamiqs, a library for GPU-accelerated and differentiable quantum simulations
Abstract — We introduce dynamiqs, an open-source Python library designed for high-performance and differentiable simulations of closed and open quantum systems. Built with JAX, dynamiqs supports CPU and GPU simulations, native parallelisation through batching, and both dense and sparse matrix representations. It also enables gradient computation through automatic differentiation. dynamiqs addresses the critical need for an accessible tool that facilitates gradient-based parameter estimation and quantum optimal control, particularly for large quantum systems. Its design targets large-scale problems while maintaining efficiency for smaller CPU-based tasks. In this talk, we demonstrate it on the optimization of a dispersive transmon readout, a main bottleneck of circuit QED with fidelity and duration typically lagging in comparison to state-of-the-art single and two qubit gates. We obtain robust and interpretable pulses and show a reduction of readout times by up to a factor 2 compared to standard readout for our realistic system parameters. By filling the gap in the availability of such tools, dynamiqs aims to accelerate quantum technology development through reliable, fast and differentiable simulations.

Speaker — Élie Genois
Title — Quantum optimal control of superconducting qubits based on machine-learning characterization
Abstract — Implementing fast and high-fidelity quantum operations using quantum optimal control relies on having an accurate model of the quantum dynamics. Any deviations between this model and the complete dynamics of the device, such as the presence of spurious modes or pulse distortions, can degrade the performance of optimal controls in practice. Here, we propose an experimentally simple approach to design optimal quantum controls tailored to the device while explicitly characterizing this quantum system. Specifically, we use physics-inspired machine learning to infer an accurate model of the dynamics from experimental data, before optimizing our experimental controls on this trained model. We demonstrate the power and feasibility of this approach by optimizing arbitrary single-qubit operations on superconducting transmon qubits using detailed numerical simulations, together with preliminary experimental results.

Speaker — Max Hays
Title — Reinforcement learning for control of superconducting qubits
Abstract — Reinforcement learning (RL) has rapidly become a powerful tool across numerous fields, both in academia and industry. This talk discusses the application of RL to superconducting quantum processors, with a focus on small-scale systems commonly found in academic laboratories. I will explore how RL benefits experimental quantum engineering in two ways: (1) achieving optimizations beyond manual capabilities, and (2) automating the calibration of experiments.

I will illustrate these applications within the context of two specific experiments. The first experiment involved optimizing the fidelity of a two-qubit gate between fluxonium qubits, where we used RL to reach a maximum fidelity of 99.922±0.009%, surpassing what was possible by hand (arXiv:2304.06087). The second experiment focused on the generation of remote entanglement between separate superconducting qubit modules. Here, RL was used to fine-tune the microwave pulses that control photon emission and absorption between the modules (arXiv:2408.05164).

Finally, I will discuss the challenges we encountered in applying RL to the calibration of superconducting qubit systems and consider how other online learning techniques might address these issues.

Speaker — David Kanaar
Title — Designing silicon spin qubit gates robust to charge noise with Hamiltonian decomposition and numerical methods
Abstract — Semiconductor spin qubits are a promising platform for quantum computing because of their compatibility with the existing CMOS industry. The largest limit on fidelity in silicon spin qubits is the fluctuating voltages caused by charge noise. Charge noise can lead to fluctuation in exchange as well as smaller fluctuations in the g-factor. By designing gates to be robust to the fluctuations caused by charge noise higher fidelity gates can be achieved. In this talk, I will present some methods for numerically finding gates robust to these fluctuations which make use of analytical tricks to simplify the optimization that is required to find the gates. The evolution of a single qubit (SU(2)) can be analytically solved. For the Hamiltonian of 2-3 simple silicon spin qubits, the dynamics map to a set of SU(2)s. This makes it possible to apply analytical methods for solving single qubit problems to creating multiqubit gates robust to charge noise efficiently. This decomposition method can be further extended to any array of qubits coupled through solely Ising coupling which is possible in semiconductor and superconducting qubits. Unfortunately, this method cannot be used if the rotating wave approximation is not valid and crosstalk terms have to be included in the Hamiltonian. However, in this case, it is still possible to apply different efficient numerical methods to create smooth control pulses such as neural networks which I will also highlight. All the presented methods show a good overview of how gates robust to charge noise in semiconductor spin qubits can be designed.

Speaker — Benjamin Lienhard
Title — Inherent and Engineered Noise-Robustness of Quantum Processors
Abstract — To fully realize the potential of quantum computing, advancements in quantum system design and control are paramount. As we edge closer to achieving effective quantum error correction, understanding the boundaries of quantum control becomes increasingly important, as these boundaries define the efficiency and scalability of error correction methods. Achieving this requires a careful balance between calibration efforts to manage parameter drift and the need for periodic recalibration. In this context, I will explore the capabilities and limitations of quantum control, focusing on developing strategies that have inherent or engineered robustness to noise. The effectiveness of these strategies hinges on their ability to withstand or compensate for unpredictable environmental disturbances. For quantum processors to process information with minimal error rates, robust measures must be in place to counteract or mitigate the inevitable presence of environmental fluctuations.

Speaker — Zac Manchester
Title — The Gray Area Between Optimal Control and Reinforcement Learning: Using Data and Models Together for Better Quantum Control
Abstract — The vast recent literature in both optimal control and reinforcement learning applied to quantum systems belies the fact that these fields are really two sides of the same coin and share a deep common history. This talk will focus on the gray area between the two, which includes such topics as adaptive control, model-based reinforcement learning, system identification, and iterative learning control (ILC). After a brief survey, we will focus on the application of ILC to quantum systems, highlighting how it can address many “sim-to-real” challenges like model mismatch, calibration, and adaptation while making efficient use of both approximate models and experimental data.

Speaker — Murphy Niu
Title — Feedforward and Machine Learning for Quantum Control towards Near-term Applications
Abstract — The rapid advancements in quantum system engineering are driving a pivotal transition into the near fault-tolerant regime, where real-time feedforward and advanced data analysis, supported by machine learning tools, are essential for achieving quantum error correction. In this review, we will explore the latest developments in leveraging mid-circuit measurements, feedforward techniques, and machine learning to significantly enhance system performance for NISQ applications and error correction experiments.

Speaker — Anders Petersson and Stefanie Guenther
Title — Time-parallel multiple-shooting for multi-qubit optimal control
Abstract — Quantum optimal control plays a crucial role in quantum computing by providing the interface between compiler and hardware. Solving the optimal control problem is particularly challenging for multi-qubit gates, due to the exponential growth in computational complexity with the system's dimensionality and the deterioration of optimization convergence. To ameliorate the computational complexity of time-integration, this paper introduces a multiple-shooting approach in which the time domain is divided into multiple windows and the intermediate states at window boundaries are treated as additional optimization variables. This enables parallel computation of state evolution across time-windows, significantly accelerating objective function and gradient evaluations. Since the initial state matrix in each window is only guaranteed to be unitary upon convergence of the optimization algorithm, the conventional gate trace infidelity is replaced by a generalized infidelity that is convex for non-unitary state matrices. Continuity of the state across window boundaries is enforced by equality constraints. A quadratic penalty optimization method is used to solve the constrained optimal control problem, and an efficient adjoint technique is employed to calculate the gradients in each iteration. We demonstrate the effectiveness of the proposed method through numerical experiments on quantum Fourier transform gates in systems with 2, 3, and 4 qubits, noting a speedup of 80x for evaluating the gradient in the 4-qubit case, highlighting the method's potential for optimizing control pulses in multi-qubit quantum systems.
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Speaker — Ryan Sitler
Title — Optimally Band-Limited Noise Filtering and Crosstalk Mitigation for Single Gates in Multi-Qubit Systems
Abstract — In the NISQ era, accurate and scalable quantum computation is hindered by noise that is often difficult to mitigate. A particularly prevalent source of noise in NISQ devices is quantum crosstalk where qubits experience always-on or gate-induced parasitic interactions. In this work, we construct optimized control sequences that mitigate temporally correlated noise and quantum crosstalk during the implementation of simultaneous single-qubit gates on multi-qubit systems. We utilize the filter function formalism to define conditions for achieving crosstalk mitigation and filtering system-environment noise. This formalism allows us to analytically derive intuitive initial conditions that are used within the Filter Gradient Ascent in Function Space (F-GRAFS) optimization framework to achieve optimal noise filtering via Slepian based control. This talk will highlight recent experimental results demonstrating the ability to design and implement crosstalk robust single-qubit control.

Speaker — Aaron Trowbridge
Title — Piccolo.jl: an integrated quantum control and calibration stack in Julia
Abstract — We are excited to release the 1.0 version of Piccolo.jl which implements a direct collocation approach for quantum optimal control and calibration. This new version gives users unprecedented flexibility in designing and solving various types of problems, from minimum time to error robustness to atom movement. We will highlight some of the new features and interface improvements that we have incorporated taking feedback from our users. We will also highlight some of the recent applications of this approach and discuss ongoing and future work.