IEEE Quantum Week 2023 – WKS05

Advances in numerical quantum optimal control and characterization methods

Workshop Agenda

2nd Floor – Regency E

Each talk is 15 minutes, with 2 minutes following for questions.

Session I

Time (PDT)	Title	Speaker
10.00 - 10.03	Welcome and introduction	Lennart Maximilian Seifert (University of Chicago, Infleqtion)
10.03 - 10.20	A Roboticist's View of Quantum Optimal Control	Zachary Manchester (Carnegie Mellon University)
10.20 - 10.37	Trainability of Quantum Optimal Control: Barren Plateaus and Overparameterization	Martin Larocca (Los Alamos National Laboratory)
10.37 - 10.54	Quantum Crosstalk Robust Quantum Control	Gregory Quiroz (John Hopkins University)
10.54 - 11.30	Moderated discussion	All participants

Session II

Time (PDT)	Title	Speaker
1.00 - 1.17	Effective and Scalable Control of Quantum Processors – Insight and Perspective	Benjamin Lienhard (Princeton University)
1.17 - 1.34	Calibration methods for numerically optimized pulses	Daniel Puzzuoli (IBM Quantum)
1.34 - 1.51	Bayesian Characterization of Quantum Computing Devices	Anders Petersson (Lawrence Livermore National Laboratory)
1.51 - 2.08	Direct pulse level compilation of arbitrary quantum logic gates on superconducting qutrits	Yujin Cho (Lawrence Livermore National Laboratory)
2.08 - 2.30	Moderated discussion	All participants

Session III

Time (PDT)	Title	Speaker
3.00 - 3.17	Closing the virtuous cycle of quantum control and machine learning	Hanrui Wang (Massachusetts Institute of Technology)
3.17 - 3.34	Piccolo.jl: An integrated quantum optimal control stack in Julia	Aaron Trowbridge (Carnegie Mellon University)
3.34 - 3.51	Iterative learning control for gate calibration	Andy Goldschmidt (University of Chicago)
3.51 - 4.08	Application of optimal control to quantum sensing: The shaken lattice problem	Lennart Maximilian Seifert (University of Chicago, Infleqtion)
4.08 - 4.30	Moderated discussion	All participants

Please see the following pages for talk abstracts.

Talk abstracts

A Roboticist's View of Quantum Optimal Control (Zachary Manchester)

The last two decades have seen tremendous advancements in the practical application of ideas from optimal control theory to robotics, with high-profile examples like SpaceX's autonomous rocket landings and Boston Dynamics' humanoid acrobatics making it into the popular culture. Fortunately, many state-of-the-art computational techniques developed for robotics applications are directly applicable to quantum systems, and many others can be made "quantum friendly" with straight-forward modifications. This talk will provide an abbreviated tour of modern numerical optimal control with pointers into the recent literature, along with several examples of applications to simple quantum systems.

Trainability of Quantum Optimal Control: Barren Plateaus and Overparameterization (Martin Larocca)

Inspired by quantum optimal control (QOC) literature, recent work has proposed a framework for analyzing the trainability of variational quantum algorithms based on the dynamical Lie algebra (DLA) of the generators of the circuits. In particular, such DLA has proven remarkably useful at predicting and understanding properties of the optimization landscapes, such as cost function concentration (a.k.a. barren plateaus) and overparametrization thresholds. In this talk, we will discuss how these results may be ported back to / impact the field of QOC.

Quantum Crosstalk Robust Quantum Control (Gregory Quiroz)

The prevalence of quantum crosstalk in current quantum devices poses challenges for achieving high-fidelity quantum logic operations and reliable quantum processing. Through quantum control theory, we develop an analytical condition for achieving crosstalk-robust single-qubit control of multi-qubit systems. We examine the effects of quantum crosstalk via a cumulant expansion and develop a condition to suppress the leading order contributions to the dynamics. The efficacy of the condition is illustrated in the domains of quantum state preservation and noise characterization through the development of crosstalk-robust dynamical decoupling and quantum noise spectroscopy (QNS) protocols. Using the IBM Quantum Experience, crosstalk-robust state preservation is demonstrated on 27 qubits, where up to a 3x improvement in coherence decay is observed for single-qubit product and multipartite entangled states. Through the use of noise injection, we demonstrate crosstalk-robust dephasing QNS on a seven qubit processor, where a 10^4 improvement in reconstruction accuracy over alternative protocols is found. Together, these experiments highlight the significant impact the crosstalk suppression condition can have on improving multi-qubit characterization and control on current quantum devices.

Effective and Scalable Control of Quantum Processors – Insight and Perspective (Benjamin Lienhard)

To achieve the dream of useful quantum computation, there are two main thrusts to make improvements: quantum system design and control. Now at the junction of realizing effective quantum error correction, the boundaries of quantum system control become an essential piece of information. Establishing the limits of efficient, scalable, and accurate quantum control can inform the efficacy and choice of different kinds of error correction. The effort of quantum system control, specifically in terms of measurements during calibration, must be sufficiently low to compensate for system parameter drift or fast enough to enable periodic re-calibration. The effectiveness of different control routines can be evaluated using theoretical and numerical studies. While theoretical models help inform on general structures of quantum control landscapes, the controllability, or the complexity of the computational effort, they are often insufficient to represent the real quantum system. Complete system characterization can lead to accurate numerical models representing the entire quantum system but are incredibly cumbersome. Model-free learning control, a laboratory-costly approach, represents the other extreme. These methods tend to be highly laborious and measurement-intensive as systems scale in size. Here, we discuss our insights and perspective on the limits and capabilities of quantum control, the role of theoretical studies, and the methods available for experimental quantum control from a measurement point of view. Finally, we explore the design of quantum control schemes that are as robust as possible to system uncertainties while remaining resource-efficient.

Calibration methods for numerically optimized pulses (Daniel Puzzuoli)

The goal of numerical quantum control is to automate the gate design process, with the promise of rapid and flexible gate design for arbitrary systems. While much work has been done on model-based numerical gate optimization, problems associated with the reliable application of the resulting pulses in experiment have received comparatively minimal attention. We will discuss these challenges and generally advocate for the view that their formalization, and the development of algorithmic solutions, is necessary for the field to achieve its potential. In terms of concrete work, we consider the problem of experimental calibration of numerically designed pulses. Specifically, we address the issue that the high-dimensional parameterizations typically required in numerical pulse optimizations are ill suited for subsequent experimental calibration, in which only a small number of parameters can realistically be tuned efficiently. To bridge the gap, we propose a model-based dimensionality reduction technique, in which a high-dimensional pulse parameterization used in optimization is transformed into a low-dimensional parameterization to be used in calibration. We will present an experimental application.

Bayesian Characterization of Quantum Computing Devices (Anders Petersson)

Motivated by the noisy and fluctuating behavior of current quantum computing devices, we outline a data-driven characterization approach for estimating transition frequencies and decay times in a Lindbladian dynamical model of a superconducting quantum device. The data includes parity events in the transition frequency between the first and second excited states. A simple but effective mathematical model, based upon averaging solutions of two

Lindbladian models, is demonstrated to accurately capture the experimental observations. A deterministic point estimate of the device parameters is first performed to minimize the misfit between data and Lindbladian simulations. These estimates are used to make an informed choice of prior distributions for the subsequent Bayesian inference. An additive noise model is developed for the likelihood function, which includes hyper-parameters to capture the noise structure of the data, see [1] for details. The outcome of the Bayesian inference are posterior probability distributions of the transition frequencies, which for example can be utilized to design risk neutral optimal control pulses. The applicability of our approach is demonstrated on experimental data from the Quantum Device and Integration Testbed (QuDIT) at Lawrence Livermore National Laboratory, using a tantalum-based superconducting transmon device.

Direct pulse level compilation of arbitrary quantum logic gates on superconducting qutrits (Yujin Cho)

Optimal control techniques can be used to directly implement any complex unitary on a quantum device. This enables us to perform a simulation faster with less error than a circuit constructed with primitive gates. In this presentation, we demonstrate that any arbitrary qutrit logic gate can be implemented with fidelity higher than 98-99 % on a single transmon chip at LLNL Quantum Design and Integration Testbed. In addition, a simplified calibration method in this work makes the use of optimal control gates more time- and resource-efficient. Lastly, we present that a more accurate fidelity of a gate can be estimated by repeating the gate in a standard quantum process tomography. Our work shows that the optimal control is a practical tool that can simulate more detailed complex quantum phenomena with high accuracy than compiling with a fixed gate set approach on the current quantum hardware. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-841474.

Closing the virtuous cycle of quantum control and machine learning (Hanrui Wang)

As the horizons of quantum computing and machine learning continue to expand, their intersection holds promising potential. This presentation explores how quantum control and machine learning can mutually enhance each other's capabilities. We first present VQP which uses variational pulse level quantum control to perform learning tasks such as variational classifier and VQE, offering better performance and scalability. Additionally, we propose machine learning methods to optimize quantum characterization processes, particularly using data-driven Transformer to estimating the fidelity of quantum program on real hardware and facilitating quantum error correction. This study underscores the prospective benefits of integrating machine learning and quantum control, which may yield significant advancements in both fields.

Piccolo.jl: an integrated quantum optimal control stack in Julia (Aaron Trowbridge)

Pade integrator collocation (PICO) is a novel quantum optimal control (QOC) approach introduced in our paper "Direct Collocation for Quantum Optimal Control". To utilize this method we present Piccolo.jl, an integrated quantum optimal control framework implemented in Julia. Piccolo.jl is a meta-package containing the following packages:
QuantumCollocation.jl: set up and solve QOC problems using PICO.
IterativeLearningControl.jl: utilize PICO solutions to correct model mismatch errors in situ on an experimental system.
NamedTrajectories.jl: intuitively and efficiently store trajectory data (underlies both of the above packages).
This presentation will comprise a walkthrough of the software interface, from creating nominal model Hamiltonians to correcting model mismatch errors on a simulated experimental setup.

Iterative learning control for gate calibration (Andy Goldschmidt)

Quantum optimal control promises to solve a wide range of critical quantum technology problems by leveraging offline, model-based, optimization frameworks. Highly-accurate system models are needed for offline optimal control to realize high-fidelity quantum operations. Complete system characterization can be challenging, especially as devices scale in size and complexity. Alternatively, data can be spent on directly calibrating optimal control waveforms. In this talk, we describe quantum interactive learning control (QILC) framework, a flexible data-driven approach for calibrating arbitrary optimal controls to quantum hardware by leveraging best-case (but potentially inaccurate) models. QILC is a powerful, novel method based on iterative learning that takes advantage of the Pade integrator direct collocation (PICO) quantum optimal control method to achieve optimal performance in situ with experimental devices.

Application of optimal control to quantum sensing: The shaken lattice problem (Lennart Maximilian Seifert)

With the design and construction of fault-tolerant quantum computers still a number of years away, a more near-time application of quantum technology may lie in the field of quantum sensing. Here the interaction of quantum systems with their environment is used to extract information about the environment’s properties – for instance the strength of a magnetic field or its acceleration with respect to a reference frame. Shaken lattice is an example to realize a quantum sensor to detect the latter: A cloud of cold atoms is trapped in a configurable optical lattice and manipulated by moving (“shaking”) the lattice. The final momentum distribution of the atoms yields information about the presence of external accelerating forces on the atoms, where the sensitivity is dependent on the shaking control. With the goal to design high-precision sensors in mind, this inevitably motivates the application of quantum optimal control techniques to find shaking protocols that improve the system’s sensitivity. In this talk we discuss the common approach derived from Mach-Zehnder interferometry and present two strategies to push the sensitivity further.