Project: Optimal Control Theory with Qiskit Pulse

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Contents

1 Introduction

Optimal control theory studies how to optimally (given an objective) manipulate a quantum system to guide a state through a desired evolution given available classical stimulus sources. Qiskit Pulse exposes control of quantum computing stimulus sources through a standardized API, making lab-level experiments possible through the cloud. In Qiskit a quantum circuit is lowered to a pulse schedule through a scheduling procedure using predefined gate to pulse schedule calibrations.

The aim of this project is to explore incorporating optimal control theory into the Qiskit compilation pipeline with the aim of enabling on the fly gate design of arbitrary unitary evolutions for applications in Qiskit Aqua. Specifically you will examine implementing GRAPE [1] on a single-qubit IBM Quantum device. This idea was explored in the work of Shi et. al. [2] (see Figure 1) with their focus on dynamic gate aggregation and design.

We will begin to build out this functionality into Qiskit. You will take the first exploratory steps of performing optimal control on actual qubits with Qiskit Pulse and then come up with a proposal for how to add this functionality to the Qiskit compilation pipeline in production.

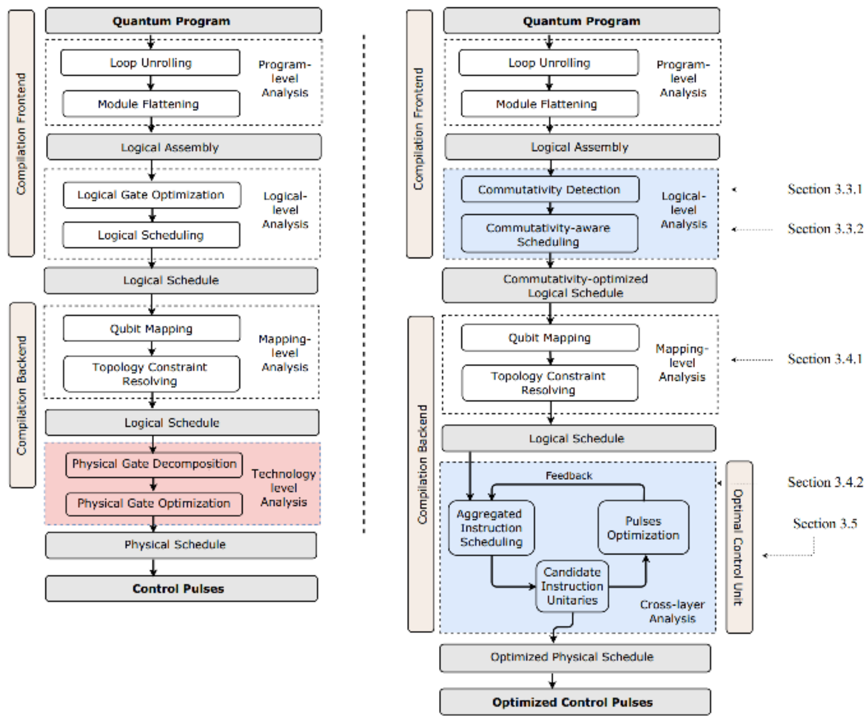

Fig. 5. The comparison between standard gate-based compilation (left) and our compilation approach (right). The key differences are highlighted by the colored areas. In the first blue box, our compiler detects potential commutativity, which opens up opportunities for much more efficient scheduling. Then our logical scheduling takes advantage of commutativity for better parallelization. In the second blue box, by iterating with the optimal control unit, the instruction aggregation procedure breaks the well-encapsulated abstraction of 1- and 2-qubit logical gates and eliminates the physical gate layer (red box) that encodes only coarse-grained hardware information.

Figure 1: Compilation pipeline proposed by Shi et. al., reproduced from [2].

1.1 Overall Goals

- Design and implement an optimal pulse control pipeline for constructing single qubit quantum gates
- Develop your physics and software skills by applying them to optimal control theory
- Gain exposure to the agile development processes and working with a full stack team across software and hardware
- Have some fun!

1.1.1 Technical Goals

- Understand in a broad sense the engineering of superconducting qubits [3, 4].
- Bootstrap control of a qubit with Qiskit Pulse. See [5].
- Model the Hamiltonian of your system and simulate it.
- Understand the goal of optimal control and how GRAPE works [1].
- Select a Python GRAPE package for incorporation into Qiskit. Examples include [6, 7, 8, 9].
- Estimate the Hamiltonian of a single qubit with Qiskit Pulse [10, 11, 12].
- Design arbitrary single qubit gates with Grape and Qiskit Pulse and characterize the gates with quantum process tomography [10].
- Hack automated gate design into the Qiskit compilation pipeline.
- Write a report reviewing the relevant underlying theory, your methodology and findings performing optimal control theory with Qiskit pulse. Include a design section proposing how to implement automated gate aggregation [2] and compilation within Qiskit and any improvements that might be required.
- Stretch goals (in no particular order other than what would be most fun for me)
  - Estimate the Hamiltonian for a two-qubit system and design a two-qubit gate with Qiskit Pulse and GRAPE.
  - Reduce the runtime of an Aqua application with automated gate design.
  - Design a gate aggregation pass in the Qiskit transpiler to work with your pulse designer.
  - Suggest how to improve the usability of the Qiskit Pulse simulator.

1.2 Workflow

Due to the nature of the situation with Covid-19 the internship will be remote. Fortunately, this project is focused on Qiskit Pulse, which gives hardware access through the cloud. To help facilitate work both Thomas Alexander and Zachary Schoenfeld will be providing supervision. Ben will partcipate in the pulse teams agile sprints, demos and board. We will hold short, daily video calls to synchronize our work. There will also be many other remote activities setup for interns to network and socialize through the IBM Quantum Internship program.

IBM Quantum intern hub: `https://w3.ibm.com/w3publisher/quantum-interns`.

1.3 Approximate Timeline (Subject to Change)

Dates: 6/5/20-8/7/20 (8 weeks)

Weeks 1, 2

- Onboard
  - Get onto w3, Slack, join standups and agile
- Gain familiarity with IBM's quantum systems and pulse-level control (ask for more papers!)
- Use Qiskit pulse to calibrate a qubit on a live device
- *Suggestion*: Draft notes as you go. This will make writing the final report easier!

Weeks 3, 4

- Model a 1q Hamiltonian with arbitrary drive pulse and simulate its evolution
  - It may also be interesting to learn how to analytically solve this Hamiltonian for simple pulses shapes (RWA, etc)
- Learn GRAPE and explore possible open source packages for implementation into Qiskit

Weeks 5, 6

- Use chosen GRAPE package and Qiskit pulse to construct arbitrary 1q gates in an optimal fashion
- Characterize these gates with Quantum Process Tomography
- Begin to integrate GRAPE into the Qiskit compilation pipeline

Weeks 7, 8

- As time permits, think about how to add gate aggregation passes [2] to your work (design is more important; can implement if time)
- Write up a report detailing the theory you learned about optimal pulse control, GRAPE and how you implemented it in Qiskit. More details provided in the **Goals** section.
- As time permits, work on the stretch goals outlined in the **Goals** section
- Offboard

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