SAND2021-14195C

Low-level Access and Collaborations: Case Studies from the Quantum Scientific Computing Open User Testbed (QSCOUT)

Christopher G. Yale
cgyale@sandia.gov

Daniel Lobser
dlobser@sandia.gov

Andrew J. Landahl
alandahl@sandia.gov

Susan M. Clark
sclark@sandia.gov

Sandia National Laboratories

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Advanced Scientific Computing Research Office. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

1 Introduction

Despite their relatively recent development, the DOE quantum computing testbeds are already generating interesting scientific output. In particular, the fact that the testbeds offer low-level access has led to several unexpected benefits. As developers and operators of the Quantum Scientific Computing Open User Testbed (QSCOUT), we will focus on specific examples of the progression of our system and interactions with some of our first round users as well as some of the challenges associated with developing a low-level access testbed.

2 Benefits of low-level access: collaboration and feedback

QSCOUT is distinguished from industrial quantum computing platforms by its low-level access to the hardware for our users (see Fig. 1 for levels of control). Along with low-level user access, we found our users also needed direct access to and collaboration with the individuals operating the QSCOUT system, and we found it was highly beneficial for best scientific results. In this section, we provide examples of the impacts of low-level access offered in our system.

2.1 Pulse-level control for better performance

Developed by our in-house software team, in tandem with the experimental system, our programming language, Jaqal, was designed to take full advantage of the features of trapped ion systems. Jaqal is transparent - allowing direct exposure to native gates; schedulable - allowing the ability to specify parallel or sequential operation of gates; and extensible - allowing pulse-level control of the gates [1]. The pulse-level control, Jaqal Pulses and Waveforms (JaqalPaw) provides users the ability to design and perform their own gates. Our software team was vital for providing access to these controls, since there was a tight integration with gate specification and the hardware unique to optical control pulses. While not directly available to first round users, the QSCOUT operators have been using the pulse-level control to better support our users, including the the choice to use (or not use) SK1 compensation schemes on the single qubit gates [2], the use of Gaussian pulse shaping on the native two-qubit gate for improved operation, and phase-error-corrected two-qubit gates [3] to mitigate phase instabilities between our single- and two-qubit gates. Now available in our second round, pulse-level control is integral to several user projects.

2.2 Co-development of gates and calibration routines

Each of our users has a QSCOUT experimentalist point-of-contact. The point-of-contact meets with the user group to not only relay data and code, but to discuss how their code operates on the system, challenges encountered in the system, and avenues to improve performance.

The QSCOUT system gained functionality throughout the first round, and our users helped drive this development. One example is the development of a composite gate, the controlled-NOT (CNOT). In an ion-trap system, the native two-qubit gate is the Mølmer-Sørensen (MS), an XX-type entangling interaction. The composition of a CNOT gate is a few single qubit gates preceding/following an MS gate [4]. With several user codes based on the CNOT, it not only became our first composite gate available, but was also incorporated into a standard calibration routine to determine the phase relationship between single- and two-qubit gates.

Additionally, our users act more as collaborators than the name “user” suggests. Our users are more than willing to work with us to tailor their code to our ion trap system. In particular, one user group found their code could be executed by either using CNOT gates or arbitrary-angle MS gates [5] as the entangling gate. By running both options, we discovered that the arbitrary-angle MS gates outperformed the CNOTs (the mechanisms behind this are under investigation). Being flexible with our users was an advantage to achieving the best results.

2.3 Lessons learned can be applied across projects

This realization regarding the enhanced performance of arbitrary-angle MS gates over CNOT gates was communicated to another user whose code bore enough similarity, via their use of CNOTs, that they plan to compose future code in a similar fashion. Similarly, due to interest in variational quantum eigensolvers, we offered exemplar codes for this anticipated use case [6], and several user groups based their code on these programs. As such, we actively co-develop experimental implementations of similar user code to foster progress across amenable users rather than sequestering each effort. We also work directly with our in-house software team for agile development of Jaqal and lower-level control software to best adapt to users' needs. Having our users, operators, and software team form a collaborative network is uniquely enabled by the open access of the DOE testbeds.

3 Challenges of low-level access

3.1 Testbed development

Building a testbed from scratch was a challenge. Our goal was to move beyond the standard experimental approach and develop a more robust, stable, and scalable platform that still allowed for low-level access and versatility. During the design phase of the project, we identified key areas that would allow us to approach a more facility-type system. This included the development of pre-aligned, bonded, and stabilized optics, a scalable and *versatile* hardware control system known as Octet, a scalable (up to 32 channels) set of systems for individual addressing and distinguishable detection, and a microfabricated trap designed for holding ion chains. While these systems are now all operational, each had significant investments [7, 8].

3.2 Levels of access

Deciding what level to allow testbed access was the first step to provide the extra controls needed. During the development of JaqalPaw, it was evident that allowing users to construct their own gates would require access to calibrated system parameters that change daily. Deciding on a minimum set of parameters that were universal enough for our users but still straightforward to calibrate (or derive from other calibrations) required careful thought.

Often low-level access and simulations are run using "research-grade" software that changes frequently as features are added. It is important to plan a dedicated effort to polish and maintain code to maintain ease-of-use to outside researchers. In QSCOUT, we found conducting seminars devoted to code use and pair programming sessions were valuable for deepening collaboration.

In the future, we plan to introduce user access to ion shuttling to allow for mid-circuit measurements. This will create its own experimental challenges due to the number of systems requiring synchronization as well as how to develop and expose low-level control of shuttling. One could also imagine another level of control for users to propose hardware changes, *assuming* sufficient modularity. This level of access is a significant challenge given the many co-design decisions to optimize QSCOUT for performance, but could be considered for future testbeds. Modular hardware might include novel ways of locking lasers or variations of control hardware.

4 Conclusion

We have described some of the valuable user interactions in the QSCOUT system that highlight the benefits and challenges of low-level access in a quantum computing testbed, as well as some anticipated and speculative advances to continue to expand this access. This versatility and configurability is relatively unique in the evolving landscape of NISQ testbeds. Preserving this approach broadens the opportunity for researchers to study a wide array of problems.

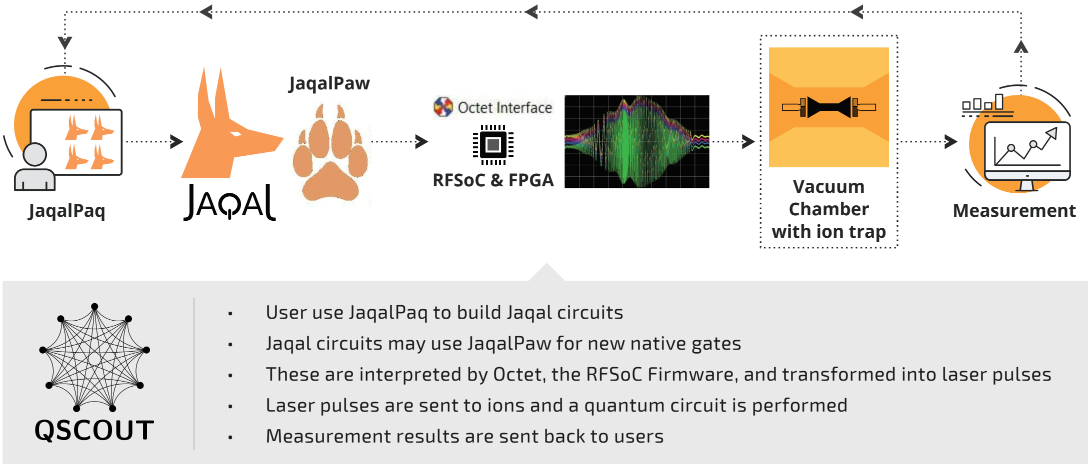

Figure 1: Description of the various levels of control on the system and specific terminology referred to in this white paper.

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