Design and Development of Superconducting-quantum-computer System

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Abstract

To scale up quantum computers to a practical size and provide them as a service, the abstraction of computing systems with a large number of quantum bits is a key step towards practical quantum computing. As a milestone to this goal, NTT, RIKEN, and collaborators launched a quantum computing service with 64 quantum bits in March 2023. In this article, NTT's efforts in this development to control a large-scale quantum computer and make it a cloud service are described. The configuration of the cloud service and future prospects of quantum computing are also explained.

Keywords: quantum computing, superconducting qubits, computer architecture

1. Introduction

By using superposition states of quantum matter, quantum computers are expected to enable high-speed computing and new types of information processing. However, superposition states are vulnerable to environmental noise and can easily change to another superposition state; therefore, quantum computing research and development (R&D) has focused on the development of devices with long lifetime of the superposition state, exploration of efficient error-correcting codes to reduce quantum noise, and analysis of quantum algorithms and its computational-performance limits.

Quantum computing has become a reality as these basic technologies have been established, and designing and developing a large-scale quantum computer that combines the research results of these technologies have been active. NTT, in collaboration with RIKEN and others, developed a quantum computer using superconducting quantum bits (qubits)[*1] and launched the first quantum-computer cloud service in Japan in March 2023. NTT has worked on the development of technology to abstract, calibrate, and automate the control of qubits and provide quantum computing as a cloud service. This superconducting quantum computer and the efforts being made to demonstrate practical quantum computing are discussed in this article.

2. Superconducting qubits

Since the matter around us obeys quantum mechanics, any two distinct states can theoretically be treated as a qubit. However, there are a limited number of systems in which we can realistically maintain the superposition state for a long time. Superconducting qubits, which use the two lowest-energy states of superconducting circuits as qubits, are promising as highly scalable quantum physical systems because they can be integrated on a substrate and maintain a long lifetime of several hundred microseconds to milliseconds.

A photograph of integrated qubits on a chip is shown in **Fig. 1**. The circular pattern in the enlarged image on the left corresponds to a single qubit. The qubits are arranged two-dimensionally on the chip

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[*1] Superconducting qubit: A physical system that uses a circuit in a superconducting state to represent the 0, 1 state of a qubit. It is known to be controllable with high fidelity while ensuring integration and considered a leading candidate for creating a scalable quantum computer.

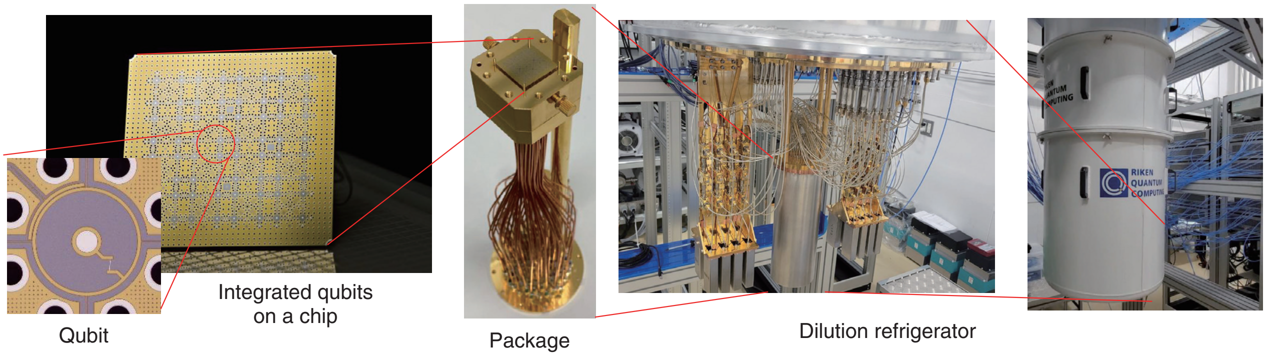


Photo courtesy of Institute of Physical and Chemical Research (RIKEN)

Fig. 1. Appearance of superconducting quantum computer.

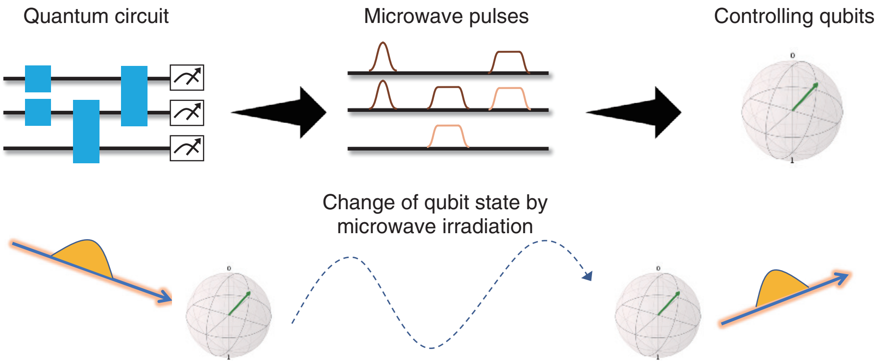


Fig. 2. Control of superconducting qubits.

and wired to the outside via the package. Since the superposition state of superconducting qubits is sensitive to thermal noise, the chip is cooled to tens of millikelvin by placing it in a dilution refrigerator.

The superconducting circuit shown in Fig. 1 is a medium that stores information and does not have the ability to compute on its own. For this reason, as shown in **Fig. 2**, microwave pulses are sent to the qubits to control them. A typical quantum-computing program is written in a representation similar to a logic circuit, called a quantum circuit. There are two types of operations on a qubit in a quantum circuit: (i) unitary operations, which change the quantum state of the qubit without obtaining information about it, and (ii) readout operations, which obtain the state of the qubit as either 0 or 1. Both operations involve qubit control with multiple microwave pulses, the shapes of which are optimized for the characteristics of the qubit and the type of operation [1]. For readout operations, in addition to microwave controls, the shape of the response microwave pulse is analyzed to discriminate whether the qubit state is 0 or 1.

These microwave controls are experimentally implemented as follows. First, the waveform of the microwave pulse is designed as digital data with classical computers in accordance with the characteristics of the quantum-circuit elements and qubit characteristics. These data are then transferred to control electronics installed at room temperature, which converts the digital signal to an analog signal that is output in the form of a microwave. The microwaves are transmitted through wires to the qubits in the dilution refrigerator. The state of qubits can be read out from the signal returned from the qubit. Thus, the returned analog waveform is converted to digital data using the electronics, and the state of qubits is discriminated with a binary classifier. By subjecting the qubits arranged in a chip to the above-described processing,

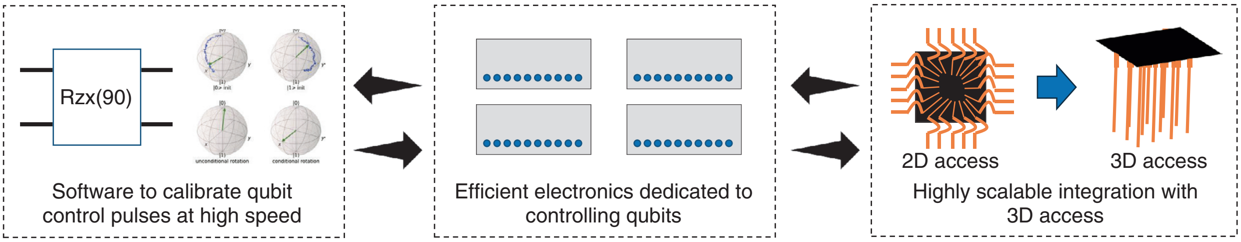


Fig. 3. Fundamental technologies supporting scalability.

it is possible to execute the desired computations and obtain results.

3. Controlling qubits

To perform quantum operations on qubits, we need to design the pulse shape of the microwaves required to control the qubits as well as the binary classification function for the readout operation. The optimal pulse shape depends on qubits' properties such as lifetime and energy gaps. Since these properties differ from qubit to qubit, the control signal must be designed for each qubit. The characteristics of the qubits can be roughly estimated at the chip-design stage, but the exact value cannot be determined without measurements on fabricated qubits. Therefore, the following two procedures must be established to carry out quantum computing with qubits. First, clarify the characteristics of the qubits through multiple measurements after cooling them in a dilution refrigerator. Second, in accordance with those characteristics, create optimal pulse shapes for each type of operations and classification functions for the readout operation. The series of experiments that ensure that the manufactured qubits can be used for computation is called "calibration."

We can calibrate qubits by hand as long as the number of qubits is small. However, as the number of qubits increases, it is not practical to design and calibrate them in an ad-hoc manner. Thus, we have made efforts to abstract large-scale quantum computing, experimentally reveal the challenges that impede scalability, and address them one by one. The three fundamental technologies that support the scalability of quantum computing shown in **Fig. 3** are explained hereafter.

The first challenge in scaling quantum computers is the problem of qubit wiring. Qubits are typically arranged two-dimensionally on the chip and individually wired from the periphery of the chip so that control signals can be transmitted to the individual qubits. However, with this arrangement, the number of necessary wires increases quadratically with respect to the chip width, while the number of wires that can be routed to qubits increases linearly to the chip width; as a result, wiring becomes more difficult when the circuit scale increases. To solve this problem, RIKEN proposed a highly scalable method, with which the control wires are three-dimensionally connected to the chip (Fig. 1), and in collaboration with Fujitsu, National Institute of Advanced Industrial Science and Technology (AIST), and National Institute of Information and Communications Technology (NICT), RIKEN has integrated qubits by using this wiring method [2].

The second challenge is to improve the efficiency of electronics. To control qubits with as few wires as possible, it is necessary to multiplex and transmit microwave signals with multiple frequencies and waveforms with a single wire. If expensive measurement equipment is used for each qubit to achieve this control, the scalability of the quantum computer becomes impractical in terms of cost and size as the number of qubits increases. The developed superconducting quantum-computer system uses the electronics optimized for controlling qubits developed under the leadership of Osaka University and others.

The third challenge is to write software to efficiently control and calibrate the qubits. As mentioned above, the method of manually characterizing qubits is known, but it is impractical to manually calibrate a large number of qubits. Since the characteristics of qubits and their controllers change over time, the quantum computer cannot be operated accurately if calibration takes too long. NTT and RIKEN have constructed a platform for controlling multiple electronics in parallel and systematically measuring qubits. Using this platform, NTT and RIKEN have also written software and protocols for automating the parallel and accurate calibration of multiple

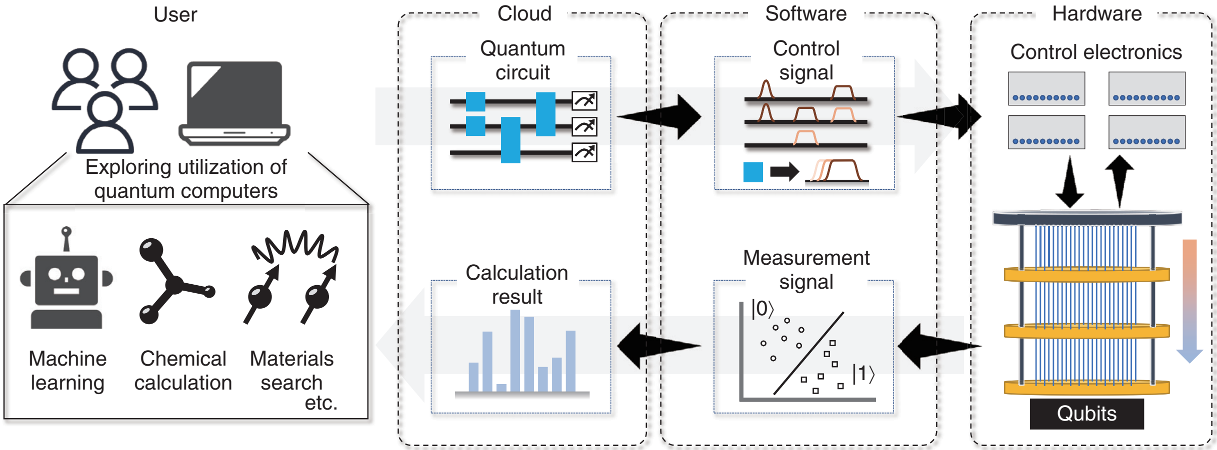


Fig. 4. Overview of our cloud service.

qubits.

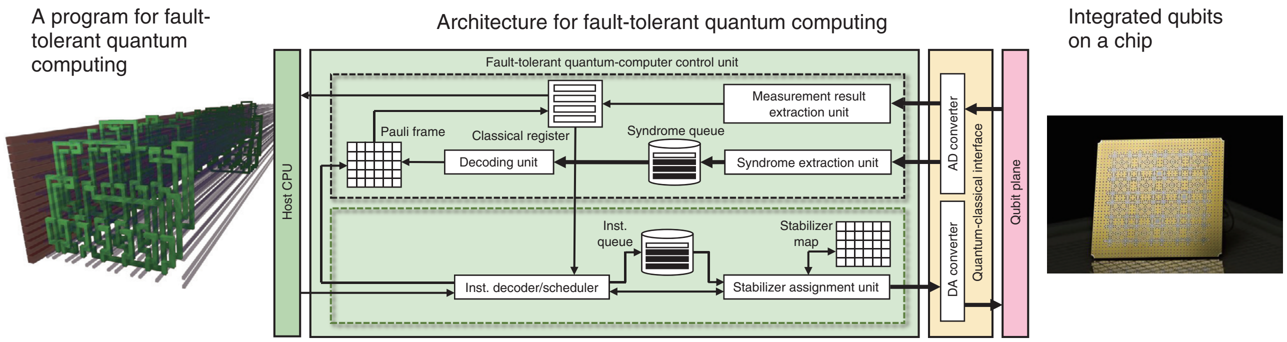
4. System abstraction and operation

The above-mentioned superconducting quantum-computer system provides the fundamental technologies to control the integrated qubits. However, to operate this system continuously as a cloud service, we need to accumulate the knowledge to maintain its stable operation. We also must create a framework for providing the service to users. The above-mentioned platform for measuring qubits works well when the qubits are manufactured ideally. In practice, however, calibration often fails for a variety of reasons. Causes of this failure range from human error, such as wrong wiring, to manufacturing problems, which cause the characteristics of the qubits to deviate so much from the designed values that they cannot be controlled. As the system is scaled up, the more difficult it becomes to identify the type and location of the cause of failure, and practical operation of the quantum computer becomes difficult. The software that oversees the entire system is therefore expected to not only operate the system in a normal state but also accurately report the cause of any anomalies at the earliest possible stage. Since there are countless types of abnormal cases, it is not easy to completely automate this procedure. Even so, NTT and RIKEN have accumulated knowledge during the development period and built a software system to efficiently find typical factors.

To provide this quantum-computing system as a service, it is also necessary to establish a web service to make it easier for users to use quantum computers. In the current design of the control software, the lowest-level representation of the program that controls the qubit is the waveform information of the microwave that controls the qubit. This representation is convenient to experimentally investigate the characteristics of qubits, but it is not realistic for users to describe their computing tasks with pulse shapes. The developed quantum computer platform provides two methods: a job-description method for directly designing the shape of a pulse for the developers of quantum computers and a method for specifying a program in the description of a quantum circuit for the users of cloud service. To provide quantum computing as a cloud service, Osaka University, RIKEN, and NTT collaborated to build the system shown in **Fig. 4**. Through this system, the user sends a program described in quantum circuits at the front end, the back-end service executes calculations using qubits with the latter method, and the measurement values, which identify measurement data, are returned to the user.

5. Future developments

Although the current cloud service is a milestone in the integration of qubits, many obstacles still have to be overcome before a practical quantum computer can be implemented. As shown in **Fig. 5**, NTT is developing technologies for a fault-tolerant quantum computer in parallel for future practical applications. The largest problem with today's quantum computers is their large noise. The best currently available



AD: analog to digital
CPU: central processing unit
DA: digital to analog

Fig. 5. Technologies for developing a fault-tolerant quantum computer.

qubits have about 0.1% error probability per gate operation, so it is impossible to reliably run large-scale quantum algorithms. It is therefore necessary to develop a technology to encode qubits using quantum-error-correction technology*2 that will execute repetitive error correction during computation and reduce the effective error rate [3]. If quantum-error-correction technology is developed, the errors and variations in the characteristics of qubits can be absorbed to some extent; accordingly, it will be possible to design and build a highly scalable quantum computer.

NTT is collaborating with various research institutes to establish a computer architecture for quantum error correction [4–8]. When we build an architecture under the assumption of error correction, the basic instruction set is defined by the characteristics of the error-correcting code rather than the device. Therefore, new compilers and software targeting fault-tolerant quantum computers are also needed. NTT constructed a compiler for long-term fault-tolerant quantum computing and proposed methods for optimizing it and software for evaluating it [9, 10]. The left side of Fig. 5 shows the actual designed program displayed as a three-dimensional graph during compiler optimization.

NTT's next goal is to integrate these system stacks we have built thus far with qubits to demonstrate a fault-tolerant quantum computer. To create a system that incorporates error correction and can process instructions at high speed as a computer, the fusion of physics and computer science is more essential than ever before. NTT will study the design of computers on the basis of cooperative design that integrates software and hardware in these cross-cutting fields. In doing so, we will lead the world in envisioning the future of practical quantum computers.

References

[1] P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, "A Quantum Engineer's Guide to Superconducting Qubits," Appl. Phys. Rev., Vol. 6, No. 2, 021301, 2019. https://doi.org/10.1063/1.5089550

[2] S. Tamate, Y. Tabuchi, and Y. Nakamura, "Toward Realization of Scalable Packaging and Wiring for Large-scale Superconducting Quantum Computers," IEICE Trans. Electron., Vol. E105.-C, No. 6, pp. 290–295, 2022.

[3] A. G. Fowler and C. Gidney, "Low Overhead Quantum Computation Using Lattice Surgery," arXiv preprint, arXiv: 1808. 06709, 2018.

[4] Y. Suzuki, Y. Ueno, W. Liao, M. Tanaka, and T. Tanimoto, "Circuit Designs for Practical-scale Fault-tolerant Quantum Computing," Proc. of 2023 Symposium on VLSI Technology and Circuits, Kyoto, Japan, 2023. https://doi.org/10.23919/VLSITechnologyandCir57934.2023.10185351

[5] W. Liao, Y. Suzuki, T. Tanimoto, Y. Ueno, and Y. Tokunaga, "WIT-Greedy: Hardware System Design of Weighted ITerative Greedy Decoder for Surface Code," Proc. of the 28th Asia and South Pacific Design Automation Conference (ASP-DAC 2023), pp. 209–215, Tokyo, Japan, 2023. https://doi.org/10.1145/3566097.3567933

[6] Y. Suzuki, T. Sugiyama, T. Arai, W. Liao, K. Inoue, and T. Tanimoto, "Q3DE: A Fault-tolerant Quantum Computer Architecture for Multi-bit Burst Errors by Cosmic Rays," Proc. of the 55th IEEE/ACM International Symposium on Microarchitecture (MICRO 2022), pp. 1110–1125, Chicago, IL, USA, 2022. https://doi.org/10.1109/MICRO56248.2022.00079

[7] Y. Ueno, M. Kondo, M. Tanaka, Y. Suzuki, and Y. Tabuchi, "QULATIS: A Quantum Error Correction Methodology toward Lattice Surgery," Proc. of 2022 IEEE International Symposium on High-Performance Computer Architecture (HPCA), pp. 274–287, Seoul, Republic of Korea, 2022. https://doi.org/10.1109/HPCA53966.2022.00028

[8] Y. Ueno, M. Kondo, M. Tanaka, Y. Suzuki, and Y. Tabuchi,

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*2 Quantum error correction: A means of effectively reducing the probability of errors occurring in the logical qubit by representing a small number of logical qubits using multiple qubits with small error probability.

"QECOOL: On-line Quantum Error Correction with a Superconducting Decoder for Surface Code," Proc. of the 58th ACM/IEEE Design Automation Conference (DAC 2021), pp. 451–456, San Francisco, CA, USA 2021. https://doi.org/10.1109/DAC18074.2021.9586326

[9] N. Yoshioka, T. Okubo, Y. Suzuki, Y. Koizumi, and W. Mizukami, "Hunting for Quantum-classical Crossover in Condensed Matter Problems," arXiv preprint, arXiv: 2210.14109, 2022.

[10] Y. Suzuki, Y. Kawase, Y. Masumura, Y. Hiraga, M. Nakadai, J. Chen, K. M. Nakanishi, K. Mitarai, R. Imai, S. Tamiya, T. Yamamoto, T. Yan, T. Kawakubo, Y. O. Nakagawa, Y. Ibe, Y. Zhang, H. Yamashita, H. Yoshimura, A. Hayashi, and K. Fujii, "Qulacs: A Fast and Versatile Quantum Circuit Simulator for Research Purpose," Quantum, Vol. 5, p. 559, 2021. https://doi.org/10.22331/q-2021-10-06-559

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