Moonshot Goal 6: PD Guidelines for PM Additional Applications

PD: Masahiro Kitagawa (Professor, Graduate School of Engineering Science, Osaka University)

1. Overview of R&D program for achieving the Moonshot Goal

As advancements in conventional computer technology are said to be reaching their limit, quantum computers are attracting attention for their ability to respond to the explosive growth in demand for various types of information processing. The realization of a fault-tolerant universal quantum computer that can perform accurate calculations while correcting quantum errors is the key to solving diverse, complex, and large-scale real-world problems at high speed. In this program, we will promote research and development (R&D) on quantum hardware, quantum communication networks, fault-tolerance, and related topics.

2. Portfolio and status of initiatives

(1) Portfolio

The realization of a fault-tolerant universal quantum computer faces the following challenges:

(a) Increasing the number of physically constrained qubits and reducing the probability of errors in individual qubits and quantum operations between qubits

(b) Connecting multiple small to medium-scale quantum computers via quantum communication to operate as a larger-scale quantum computer

(c) Finding a quantum error correction scheme suitable for the topology and strength of the coupling between qubits, and making the fault-tolerant threshold as high as possible for a given number of qubits.

To overcome these challenges, we will promote R&D projects in the three categories of 1) quantum hardware, 2) quantum communication networks, and 3) fault tolerance, and aim to realize a fault-tolerant universal quantum computer through organic collaboration.

(2) Status of current initiatives

At present, superconductivity, ion trap, and optical quantum are working as noisy intermediate-scale quantum computers, but the hardware to realize a fault-tolerant universal quantum computer, which requires a large number of qubits, is unknown.

Therefore, in the quantum hardware category, we are competitively promoting four promising projects: superconductivity (PM Tsuyoshi Yamamoto), ion trap (PM Hiroki Takahashi), photonic(PM Akira Furusawa), and semiconductor (PM Hiroyuki Mizuno). In the quantum communication network category (PM Hideo Kosaka and PM Takashi Yamamoto), two projects are being competitively promoted while encouraging complementary cooperation and collaboration with the quantum hardware projects. In the fault tolerance category, from the standpoint of the theory/software (PM Masato Koashi), we are promoting R&D to establish guiding principles for achieving the goal in cooperation with R&D projects in the quantum hardware and quantum communication network categories.

(3) Current research and development issues for achieving the goal

With the Moonshot Goal 6, Japan is the first country in the world to declare the aim of realizing a fault-tolerant universal quantum computer by 2050, and to demonstrate the effectiveness of quantum error correction by 2030. Recently, foreign companies have set the ambitious goal of realizing 1,000 logical qubits by 2030, and international competition to achieve quantum advantage, which is the ability to perform useful quantum computations that exceed the capabilities of classical computers through quantum error correction, is intensifying. Furthermore, there is a growing social need for a fault-tolerant universal quantum computer that can perform large-scale calculations beyond supercomputers, such as decarbonization for solving global warming.

Realizing a fault-tolerant universal quantum computer requires the capacity to perform quantum error correction and seamlessly expand the number of qubits. There is an upper limit to the number of qubits that can be realized with a single piece of quantum hardware, determined by the physical size of the hardware. For expanding the number of qubits beyond the upper limit, multiple quantum hardware devices may be connected via a quantum communication network and operated as a distributed quantum computer. However, because of the overhead of communication, a desirable outcome is to realize as many qubits as possible in each individual quantum hardware and a certain number of logical qubits by quantum error correction.

Against the backdrop of global competition, the following points, which are currently lacking, must be strengthened to achieve quantum advantage through quantum error correction as well as fault tolerance.

1) Quantum hardware

As mentioned above, there is an upper limit to the number of physical qubits that can be accommodated by a single piece of quantum hardware. Realizing as many logical qubits as possible by increasing the upper limit and reducing the quantum error would be desirable. From this viewpoint, the preferable approach is to have quantum hardware that can expand the number of physical qubits with a small physical size and small quantum errors to the upper physical size limit in an arrangement that is highly compatible with quantum error correction. Considering the scenario of global competition, scaling up to 1,000 physical qubits or 100 logical qubits or more is desirable. Based on the results of basic research and the efforts of major domestic R&D projects, such as the Quantum Leap (Q-LEAP) Flagship Program, it is necessary to strengthen R&D of solid-state and atomic systems using methods and approaches that are different from existing R&D projects and those that have the potential to realize physical qubits with small physical size and small quantum errors.

2) Quantum communications network

To reduce the communication overhead of a distributed quantum computer and achieve a large scale of operation, researchers should upgrade the quantum communication network that connects quantum hardware. The quantum communication protocols required to efficiently operate a distributed quantum computer by interconnecting a large number of quantum hardware are issues that are common to large-scale quantum communication networks (quantum internet). Quantum repeaters, including quantum interfaces, quantum memory, etc., which are being studied and developed in quantum communication networks, are elemental technologies for the quantum internet. It is necessary to accelerate the realization of a large-scale distributed quantum computer by building a testbed using these technologies and empirically studying and developing quantum communication protocols.

3) Fault tolerance

A fault-tolerant universal quantum computer requires classical information processing with fast error syndrome analysis for quantum error correction. In this R&D program, we have begun R&D on the theory and software of quantum error correction and fault tolerance. However, achieving quantum advantage and fault tolerance through quantum error correction would require R&D of large-scale and high-speed information processing systems (hardware and software) and implementations for quantum error correction. Some R&D projects for quantum hardware have started this on a small scale, but as global competition intensifies, it will be necessary to promote R&D for large-scale error correction systems in parallel with R&D for quantum hardware.

3. R&D themes and their requirements in the application

(1) R&D for promising quantum hardware (solid-state systems) for acquiring fault tolerance

This R&D theme calls for projects concerning solid-state quantum hardware that can be expanded to a scale sufficient for demonstrating error correction by 2030 using two-dimensional expanding high-performance qubits with low error rates in an arrangement suitable for quantum error correction. Specifically, we expect proposals for solid-state qubits that can be scaled up to at least 1,000 physical qubits as single piece of quantum hardware.

In this R&D program, we are conducting R&D projects that aim to realize a highly integrated silicon quantum computer by making full use of silicon semiconductor manufacturing technology and its peripheral technologies. Notably, R&D aimed at achieving this goal through approaches that improve the integration of high-quality qubits on a small scale of a few bits in semiconductor systems is conceivable, but proposals for R&D projects for scalable quantum hardware suitable for fault tolerance in solid-state systems as well as semiconductors are also welcome.

In the semiconductor focused proposal, given that the goal of large-scale qubit integration is common, we expect to collaborate on common issues while competing with existing semiconductor-based R&D projects. We also expect to collaborate with a theoretical/software R&D project on quantum error correction and fault tolerance, and with a quantum communication network R&D project on quantum connections between quantum hardware.

Milestones, which are verifiable quantitative goals set in the proposal, and collaboration with existing R&D projects will be adjusted in the refinement period after the proposal is accepted.

(2) R&D for promising quantum hardware (e.g., atomic systems) for acquiring fault tolerance

This R&D theme calls for R&D projects on atomic quantum hardware that can be expanded to a scale sufficient to demonstrate error correction by 2030 by two-dimensional expanding high-performance qubits with a small error rate in an arrangement suitable for quantum error correction. Specifically, we expect proposals for atomic qubits that can be scaled up to at least 1,000 physical qubits as a single piece of quantum hardware.

For example, in recent years, an analog quantum simulator with several hundred physical qubits has been realized in a cooled atomic system, and has been attracting attention as a large-scale qubit system. R&D of such a system that can operate as a quantum computer capable of quantum error correction is conceivable. Proposals for R&D projects for scalable quantum hardware suitable for fault tolerance outside of solid state and atomic systems are also welcome.

In proposing an atomic qubit array, we expect to collaborate with the existing R&D project on quantum communication networks (PM Takashi Yamamoto), which has started R&D of an atomic qubit array. We also expect to collaborate with the R&D project on theory and software regarding quantum error correction and fault tolerance, and with the R&D project on quantum communication networks regarding quantum connections between quantum hardware.

Milestones, which are verifiable quantitative goals set in the proposal, and collaboration with existing R&D projects will be adjusted in the refinement period after the proposal is accepted.

(3) Empirical R&D for large-scale quantum communication networks

This R&D theme calls for R&D projects that conduct empirical R&D of large-scale quantum communication network technology or system construction that enables to communicate high quality and high density quantum information, using quantum communication network testbed (either new or existing).

To establish a quantum communication network testbed at an early stage, we will be working closely with existing communication network R&D projects and utilize the results of these R&D projects. This work is also expected to contribute to the realization of a large-scale distributed quantum computer by collaborating with the R&D projects on theory and software and on quantum hardware.

Milestones, which are verifiable quantitative goals set in the proposal, and collaboration with existing R&D projects will be adjusted in the refinement period after the proposal is accepted.

(4) Information processing system R&D for quantum error correction

This R&D theme invites R&D projects for developing classical information processing systems that can perform high-speed error syndrome analysis for quantum error correction to realize a fault-tolerant universal quantum computer. We seek proposals that implement large-scale, high-speed information processing systems (hardware and software) that accelerate the realization of quantum superiority and fault tolerance through quantum error correction. Specifically, to achieve quantum superiority through quantum error correction by 2030, we welcome proposals for the implementation of quantum error correction systems that enable the use of 100–1000 logical qubits in quantum algorithms, and that are scalable to fault-tolerant and universal quantum computers of 1,000 logical qubits or more, including distributed systems. However, the scale of implementation and configuration of the proposed systems are not limited to this.

We look forward to your contribution to the realization of quantum superiority and fault tolerance through quantum error correction as an R&D program, in close collaboration with the R&D projects on theory and software, quantum hardware, and quantum communication networks.

Milestones, which are verifiable quantitative goals set in the proposal, and collaboration among existing R&D projects will be adjusted during the refinement period after the proposal is accepted.

(Reference)

・Moonshot Goal 6 website
https://www.jst.go.jp/moonshot/en/program/goal6/index.html

・Moonshot Goal 6 Kickoff Symposium (held March 11, 2021)
https://www.jst.go.jp/moonshot/news/20210311.html

・Moonshot International Symposium for Goal 6 (held April 23, 2021)
https://www.jst.go.jp/moonshot/en/news/20210423.html

(Reference) PD's Supplement in FY2020 PM Application

PD: Dr. KITAGAWA, Masahiro (Professor, Institute for Open and Transdisciplinary Research Initiatives, Osaka University)

1. Policy for Selection and Content of Proposal

(1) Policy for Selection

Please submit a proposal of a scenario for the set MS Goal, "Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050". Including both the concept of "forecasting" that predicts the future from current society and technology, and the concept of "backcasting" that suggests what to do now considering 2050 society as a reference point, the proposal should contain an outlook for 3 years, 5 years and 10 years after PM selection, and an outlook for 2050. Please elaborate on feasibility in terms of achieving the MS Goal by 2050, implementing and adapting to society, being challenging and innovative, and integrating ELSI considerations for societal acceptance.

(2) Proposal content

In order to realize the MS Goal's fault-tolerant universal quantum computer, we think it necessary to integrate a huge number of qubits, provide redundancy using quantum error correction codes, and reduce the quantum error to below the fault-tolerant threshold.

Therefore, as shown in the R&D concept, as a 2030 milestone we aim to develop a certain scale of quantum computer and demonstrate the effectiveness of quantum error correction. We assume that R&D projects will be implemented in three categories: '1) hardware', '2) communication networks', and '3) theory and software'. Specifically, we would like R&D projects on '2) communication networks' and '3) theory and software' to work together to determine the feasibility of multiple promising 1) 'hardware' R&D projects, and conduct R&D to achieve the MS Goal.

Therefore, please make an R&D project proposal in any of the categories 1) to 3) as follows.

1) Hardware

We call for multiple R&D projects based on different physical systems as promising hardware for realizing a fault-tolerant universal quantum computer.

2) Communication network

We call for a R&D project for a quantum communication network required to realize a distributed large-scale quantum computer by quantumly combining hardware of a quantum computer that is not necessarily a large-scale one.

3) Theory and software

We call for a R&D project on theory and software for realizing a fault-tolerant universal quantum computer.

Milestones aimed to be achieved at 3 years, 5 years and 10 years from the time of PM adoption can be set in the category of hardware, communication networks, or theory and software. However, in the proposal please reflect on what developments you expect from the other categories, and how your research will contribute to realizing a fault-tolerant universal quantum computer by 2050.

2. Policy for promoting R&D

(1) Portfolio management

Taking into account the relationship between multiple R&D projects, portfolio management requires collaboration and competition between PMs. Therefore, for the period after being selected as a PM, the milestones to be achieved 3, 5 and 10 years from the time of being selected will be made clear, and a review of the progress and budget plan shall be conducted in consultation with the PD.

In particular, during the elaboration period of each R&D project, each R&D project in the three categories described in section 1.(2) will cooperate with each other to coordinate R&D project plans so that R&D can make steady progress to achieve the MS Goal. During the implementation of R&D projects, please carry out R&D in close cooperation with each other.

R&D will be conducted effectively toward the realization of a fault-tolerant universal quantum computer by promoting complementary R&D, while taking into full account of the results of related domestic major R&D projects such as the Optical and Quantum Leap Flagship Program (Q-LEAP).

(2) Industry – academia collaboration

To realize a fault-tolerant universal quantum computer, I think that it is also necessary to combine various technological elements from materials, microwaves, optics, processes cultivated in semiconductor integrated circuits, design, packaging, and peripheral circuits. Therefore, we welcome proposals that from the early stages of R&D work closely with private companies that possess these kinds of technologies, know-how and human resources.

(3) Development of human resources in science and technology

In order to achieve the goal "Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050", it is essential from now on to build a long-term vision and increase the number of human resources. Therefore, in addition to promoting R&D, we call for active contributions to human resource development.