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The Future of Quantum Information: Challenges and Vision

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Abstract

Quantum information has passed the theoretical research period and has entered the realization step for its application to the information and communications technology (ICT) sector. Currently, quantum information has the advantage of being safer and faster than conventional digital computers. Thus, a lot of research is being done. The amount of big data that one needs to deal with is expected to grow exponentially. It is also a new business model that can change the landscape of the existing computing. Just as the IT sector has faced many challenges in the past, we need to be prepared for change brought about by Quantum. We would like to look at studies on quantum communication, quantum sensing, and quantum computing based on quantum information and see the technology levels of each country and company. Based on this, we present the vision and challenge for quantum information in the future. Our work is significant since the time for first-time study challengers is reduced by discussing the fundamentals of quantum information and summarizing the current situation.

Keywords

Quantum Information, Quantum, Sensing, Computing, Communication

1. Introduction

We are living in the information and communications technology (ICT) era. Information has potential value in the ICT era, and it is used in a variety of ways such as business revenue from processing data and prospects for the future. In the ICT era, domestic and international companies have used their business models such as artificial intelligence (AI) and machine learning (ML) for their corporate strategy.

Computational processing in today's ICT environment uses only the allocated computing resources. In the current digital computer environment, the computational processing speed/time is determined relative to the number of resources. Digital data has many time problems due to the limitation of bits of 0 and 1 based on transistors [1]. This is because it must be done with bits in the process of storing or processing data. Nonetheless, using quantum ICT in this process allows more computational processing in the same resource environment. Therefore, quantum information technology can be used in existing ICT environments, enabling rapid computational processing, detailed measurement, and powerful encryption,

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so quantum cryptography research is expected to affect the entire industry.

Quantum information is a new paradigm that uses the quantum theory to replace the current computing. As the basis of quantum information, quantum means the minimum amount that a physical quantity can have using unique characteristics such as superposition, entanglement, squeezing, coherence, etc., which can store and process more data than the base [2]. This means that one can process more than digital data consisting of 0 and 1. In quantum information, the unit of processing data is expressed in Qubit [3]. If quantum technology is applied to the information and communications sector, it is the next-generation information and communication technology that can overcome the limitations of existing digital computers, such as data transmission, cryptographic key generation, and high-speed computing (i.e., supercomputing).

All digital devices such as computers and mobile devices, which are closely used in everyday life, represent and compute all data in bits. The complexity corresponding to the N bit is required to compute the two-part bit. As mentioned earlier, the resources and time invested are proportional to the complexity, which is physical, spatial, and cost-effective. Because traditional computing environments are impossible, studies incorporating the quantum theory are noteworthy. In other words, the quantum theory that Werner Heisenberg [4] suggested in the past has begun to be incorporated into practical research.

Today's global quantum information communication market is expected to reach approximately $65 billion by 2030 from $570 million in 2019, assuming an annual growth rate of 50.6% [5]. Quantum information is an important area of research that cannot be ignored, as evidenced by the rapid growth of the market. The quantum information market is likely to grow further as it can replace the traditional computing market.

Our study intends to understand quantum information communication, quantum sensing, and quantum computing among quantum information fields. It is a meaningful task to look at from an institutional, technological perspective and to sort out the studies that have been conducted so far.

Quantum information is a discipline. This means that there are countless detailed research fields and numerous studies. We would like to present the flow of research on key technologies and the vision for the future so that those who are new to quantum information find it little bit easier and gain more access to quantum information.

In summary, this paper makes the following contributions:

- Explaining the flow of quantum communication, quantum sensing, and quantum computing research related to quantum information.
- Discussing bilateral technologies by country/business.
- Presenting the vision and challenge for quantum information.

The rest of this paper is structured as follows. Section 2 summarizes the basic knowledge of the techniques associated with quantum information and explores current studies. Section 3 describes the status of research support in the country and the research trends of companies. Section 4 presents and discusses challenges and visions related to quantum information. Finally, we present the conclusion in Section 5.

2. Status of Quantum Information

We explore the basic knowledge and current level of technology for quantum information-related research in three categories: quantum communication, quantum sensing, and quantum computing.

Quantum communication is a technology that supports communication by constructing more secure networks than the existing networks by utilizing quantum states [6]. Here, encryption-based technologies underlying the network are being studied. Currently, we mainly study [7,8] the quantum key distribution (QKD) approach. Eventually, the key exchange must configure the network to send data. Therefore, we aim to construct a quantum communication network infrastructure eventually [9].

Second, quantum sensor/imaging is a field of research that uses quantum phenomena to measure physical quantities [10]. Technology for new ultra-precision quantum sensors improves the precision of existing sensors/imaging. Recently, many studies [11,12] have been conducted regarding autonomous driving. Due to the nature of the digital data consisting of 0 and 1, however, the measurement range of the sensor is limited. Therefore, the goal is to address this so that more detailed measurements can be made [13,14].

Laurie et al. [15] summarized examples of quantum sensing in single-mode and two-mode skew states. Many quantum optics sources have confirmed limiting noise to less than 10 dB, and they have published a comprehensive, focused study on factors that reduce the loss rate of noise. The intensive study of these factors is important for optimizing the cost, size, weight, and power of quantum sensors.

Pirandola et al. [16] investigated and tested the methods required to implement and measure quantum sensing. We discussed the verification methods of the measured values and contributed significantly by presenting the challenges to the methods that could improve them.

Third, quantum computing aims to overcome the information processing limitations of conventional digital supercomputers to improve the performance of innovative computational processing in various environments. Quantum computing can solve the problem of data computation time in today's supercomputers by dramatically reducing the time spent on big data analytics, AI, and ML [17,18].

The main studies of quantum computing are noisy intermediate scale quantum computer (NISQ) and quantum convolutional neural network (QCNN). In the past, the unit of quantum computing has exceeded the single-digit qubit study [19], reaching the commercialization stage with tens to hundreds of cubits. This system is called NISQ [20]. Convolutional neural network (CNN) models are the most used learning models in deep learning. CNN models exploit the correlation information between pixels and surrounding pixels. QCNN is a model that defines layers in quantum systems behaving similarly to CNN structures [21].

We can confirm that quantum information-related research is currently focused on areas that can be applied in real life, rather than basic theory research.

3. Global Quantum Technology

This section describes the status of bilateral research by country and company. Quantum information research has different support policies, expectations, and initiatives due to the high entry barriers depending on infrastructure. The government-led study also covers basic research on quantum information. On the other hand, companies research quantum information in terms of business models. In fact, there is a major study of quantum computing that can handle enterprise information.

The study on quantum information is not an area that has drawn attention from the beginning. The encryption approach, which is an important foundation across industries, is used to store private and valuable information. The traditional method was to use supercomputing to find the key value used for encryption. Still, the emergence of quantum information technology has surpassed supercomputing capabilities, suggesting that the key values used in classic encryption can be found. QKD prototypes have identified threats from traditional encryption [22], predicting them as one of the main factors of government interest because they can be exploited across industries.

Through *A Federal Vision for Quantum Information Science* [23], the US government is studying quantum information and communication technologies such as Defense Advanced Research Projects Agency (DARPA), National Science Foundation (NSF), Intelligence Advanced Research Projects Activity (IARPA), and National Academy of Sciences (NAS) [24].

The National Strategic Overview of Quantum Information Science was announced as a strategic R&D approach at the national level [25]. Through this, the science-first approach to quantum information science (QIS) was adopted to strengthen basic research in quantum fields such as quantum computing and quantum sensing and promote cooperation with the industry actively to foster human resources in QIS. The establishment of the National Quantum Initiative Act subsequently laid a legal and institutional foundation; as part of this, the National Quantum Coordination Office of the National Science and Technology Council announced “A Strategy Vision for America” [26, 27] under the NSTC Subcommittee on Quantum Information Science (SCQIS). Through this strategy, we focus on building the foundation for quantum device networking and predict that the nation’s economy and security will be improved through innovative applications of quantum devices. The NSF and the US Office of Science and Technology Policy said that they will invest $90 million in quantum information science over the next 5 years to create three new research centers.

Aside from the United States, Canada, under the leadership of its government, has formed an industrial, academic, and research infrastructure, and it is making continuous investments. In particular, Canada is leading intensive research through research institutes such as the Natural Sciences and Engineering Research Council of Canada (NSERC), Canada Foundation for Innovation (CFI), Canadian Institute for Advanced Research (CIFAR), and Canada First Research Excellence Fund (CFREF) based on investment of more than $1 billion [28,29].

Europe published the Quantum European Project in 2006 and issued a quantum information communication statement, setting mid- to long-term R&D targets for various quantum technologies. At the 2016 Quantum Technology Flagship Conference, the EU’s joint mid- to long-term research and development strategy, Quantum Manifesto, was announced [30]. According to the Quantum Manifesto, the EU would establish joint mid- to long-term R&D objectives for quantum technology, dividing quantum information technology into four areas: quantum communication, quantum simulation, quantum sensor, and quantum computer [30].

In the UK, as part of the National Quantum Technologies Program project, the Engineering and Physical Science Research Conference (EPSRC) invested $180 million to build 4 Quantum Technology Hubs connecting 17 UK universities and 132 companies. It aims to develop a variety of quantum sensor and measurement technologies that can be commercialized by UK businesses as well as support the expansion of quantum-related infrastructure and training of professionals [31].

The Chinese government began supporting quantum information research in 2006 with the support of quantum control technology and the National Council’s Notice on the Publication of the National 13th 5-Year Plan for Information [32,33].

In 2017, the world’s largest quantum information science laboratory was built in Anhui Province following investment of about $13 million for two and a half years; an intercontinental QKD was demonstrated between Beijing and Vienna, starting with a quantum communication network with distance of 2,000 km [34].

Japan started developing quantum information communication technology as the National Institute of Information and Communications Technology (NICT) established a quantum cryptographic test bed. It has established a roadmap, and it is developing technology by 2040. It also provides $43 million in financial support through the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) program, announcing that the Start of Core Research for Evolutional Science and Technology (CREST), the research creation project of Rikagaku Kenkyusho, Institute of Physical and Chemical Research (RIEKN), and Japan Science and Technology Promotion Agency, will provide $22 million annually [35,36].

The South Korean government started supporting quantum information and communication research through mid- to long-term strategies for quantum information communication in 2014 and announced that it will provide a total of $44.5 million for quantum information communication core technology development by preparing a plan for quantum computing technology development in 2019 [37]. A task-force team consisting of industry-academe experts was formed to establish a comprehensive plan for promoting quantum information and communication in 2019, and such will include infrastructure and institutional support measures for quantum information and communication research such as predicting demand for research and development, training quantum information and communication research personnel, and pursuing industrial development [38].

It also announced that it would provide $49.3 million for the project to create a quantum information science R&D ecosystem based on the quantum information research support center and foster research personnel [39]. In addition, research institutes such as the Quantum Technology Institute of KRISS and Center for Quantum Information of the Korea Institute of Science and Technology are conducting quantum information processing and quantum information communication research.

As such, the government spends its research budget and designates state institutions to conduct active research. This can be regarded as an attempt to gain the upper hand in quantum information technology since preoccupying quantum information technology provides economic benefits.

As discussed earlier, companies are making intensive research investments in quantum computing in terms of business models. Table 1 shows the research and development of quantum information technology by global IT companies.

Google [40] has established, together with the National Aeronautics and Space Administration (NASA), a quantum artificial intelligence laboratory, achieving Quantum Supremacy ahead of the computational processing power of supercomputing.

Intel [41] unveiled Horse Ridge II, a highly integrated system-on-chip (SoC) for quantum computers, at the “Intel Labs Day 2020” conference. This allows Intel to focus on chipset development.

IBM [42] unveiled its quantum computing system and programming language “QSAM.” We are looking at the hardware and software market by developing full-stack quantum computer design.

Microsoft [43] is working with quantum hardware manufacturers IonQ, Honeywell, and QCI to develop quantum computing. We also drew attention by announcing Q#, a quantum computing programming language, as a company characteristic of software.

Amazon [44] invests in quantum computing technology development companies D-Wave, IonQ, and Rigetti for Amazon Web Service (AWS) as its cloud services.

Major IT companies that can invest existing budgets are developing quantum information technology through their own R&D, and they are also co-working with quantum information development companies to provide investment support. In addition, start-up companies related to quantum information technology such as D-Wave, Rigetti, and IonQ are conducting more active research with government and company budgets.

Table 1. The state of quantum information technology by company

Company	Technology
Google	Establishment of NASA and quantum artificial intelligence research center 52 Qubit development
IBM	Full stack Desing Computer development Published quantum programming language “QSAM”
Microsoft	Focus on Quantum S/W development Cooperation with IonQ, Honeywell, and QCI
Intel	2nd generation quantum chip Horse Ridge II released
SAMSUNG	Quantum computing investment and technical support
Amazon	D-Wave, Rigetti, IonQ investment support for use in AWS
D-Wave [45]	2000 qubit quantum computer development
Rigetti [46]	Quantum computing technology research and development
IonQ [47]	Development of quantum computer using the ion trap method

4. Quantum Information: Challenge and Vision

This section aims to present the challenges and visions necessary for future quantum information research. Currently, quantum information research has a technological gap due to national budget differences, as identified in Section 3. We would like to present the challenges and visions necessary from an institutional and technical perspective for research on quantum information as the next generation of ICT.

Testbed: Quantum information is a research area that requires hardware equipment. This will soon require a huge budget and make entry barriers higher; hence the need to resolve the entry barrier through the construction of the test bed.

There are start-up companies based on quantum information research such as D-wave, IonQ, Rigetti, and IDQ. Leading research by large companies and countries is an important factor in the mid- to long-term aspects, but it is necessary to establish a consortium to conduct detailed studies actively. We need to build testbeds and support research and experimental environments to foster startups in line with the trend of the times for quantum information.

Global Roadmap: Currently, quantum information research has different national research directions. This suggests that it is leading government-led research by unveiling mid- to long-term R&D roadmaps. In addition, the direction of detailed quantum research focusing on different countries is different. As a huge budget is spent on quantum information research, however, a consortium on quantum information research in each country is needed to reduce global economic losses. Through the consortium, it is necessary to present a roadmap that can coexist and create synergy effects along with resolving the technology gap caused by quantum information research.

Standardization: Standardization and certification bodies for quantum information technology are required. If the technology gap preoccupies the standard of quantum information, the technology monopoly creates a larger technology gap. In addition, interworking between hardware platforms and software platforms should be prepared to avoid technical problems caused by standards in quantum information, which is critical. Consequently, national consultations are needed with international standards bodies related to quantum information and with technology certification methods.

Prepare for the convergence of quantum computing and digital computing industries: Each detailed study of quantum information, i.e., quantum computing, quantum communication, and quantum sensing, is organically connected. A software build is needed on top of the hardware platform. Currently, companies are studying cloud services based on quantum computing as their main model. Like the current cloud computing, quantum computing can solve computational processing problems for quantum communication and quantum sensing.

We identify not only institutional aspects but also major challenges and visions for quantum communication, quantum sensing, and quantum computing from each detailed technical perspective.

Quantum communication: The field of quantum communication is focused on the cryptographic base. The first application is the financial sector, where security is a priority with respect to encryption [48]. The quantum communication sector will become a new infrastructure foundation, replacing traditional networks. Therefore, research on network equipment supporting quantum communication is also needed.

Quantum sensing: Quantum sensing is mainly studied to overcome the limitations of lidar sensors. It is expected to have an overall impact on the industry as a study to measure objects that have not been measured in the past or to measure more detailed units. It is an underlying technology that can be used in relatively wide fields compared to quantum communication and quantum computing. Sensors exist in all devices used in the ICT era where we live today. Therefore, it is an area that can have the greatest market power in quantum information research.

Quantum computing: IT companies are scrambling to research and develop quantum computing as it can overcome the computational processing speed limit of the existing supercomputing. It is used primarily for big data analysis and ML, which is currently the basis of supercomputing, and is expected to replace digital computers in the future. Today, most IT companies are developing full stack based on systems that make up quantum computing, providing the most accessible and usable environment for end users. The qubit computation of quantum computing will be developed continuously.

The challenge in quantum computing is a field of research on quantum algorithms [49] that replace the existing algorithms. Existing algorithms are configured based on bits, making them difficult to use in quantum computing, which is processed by qubit. We also need to prepare for quantum computing attacks on existing security systems. As we all know, the computational processing speed of quantum computing goes beyond supercomputing. As a result, the bit-based encryption method is easily disabled; hence the need to prepare for this.

5. Conclusion

We have identified quantum communication, quantum sensing, and quantum computing related to quantum information research. Currently, quantum information is a state-led, next-generation industry, and it has a lot of growth potential. We also looked at the challenges and visions from the institutional and technical perspectives of quantum information research in the future.

Quantum information is a revolution that will bring about a new paradigm in the ICT era. The Internet and GPS, which were studied for use in the closed military environment in the past, have become essential elements in our lives. As such, quantum information research is a revolution that will bring new paradigms to the ICT era. Thus, we need to be prepared for policies, institutions, budgets, challenges, etc. on quantum information research.

The content presented in our paper has only provided a big picture of quantum information, but more research is needed on detailed research. We would like to present the level of technology and challenges for each detailed study of quantum research as a future research.

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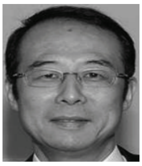

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