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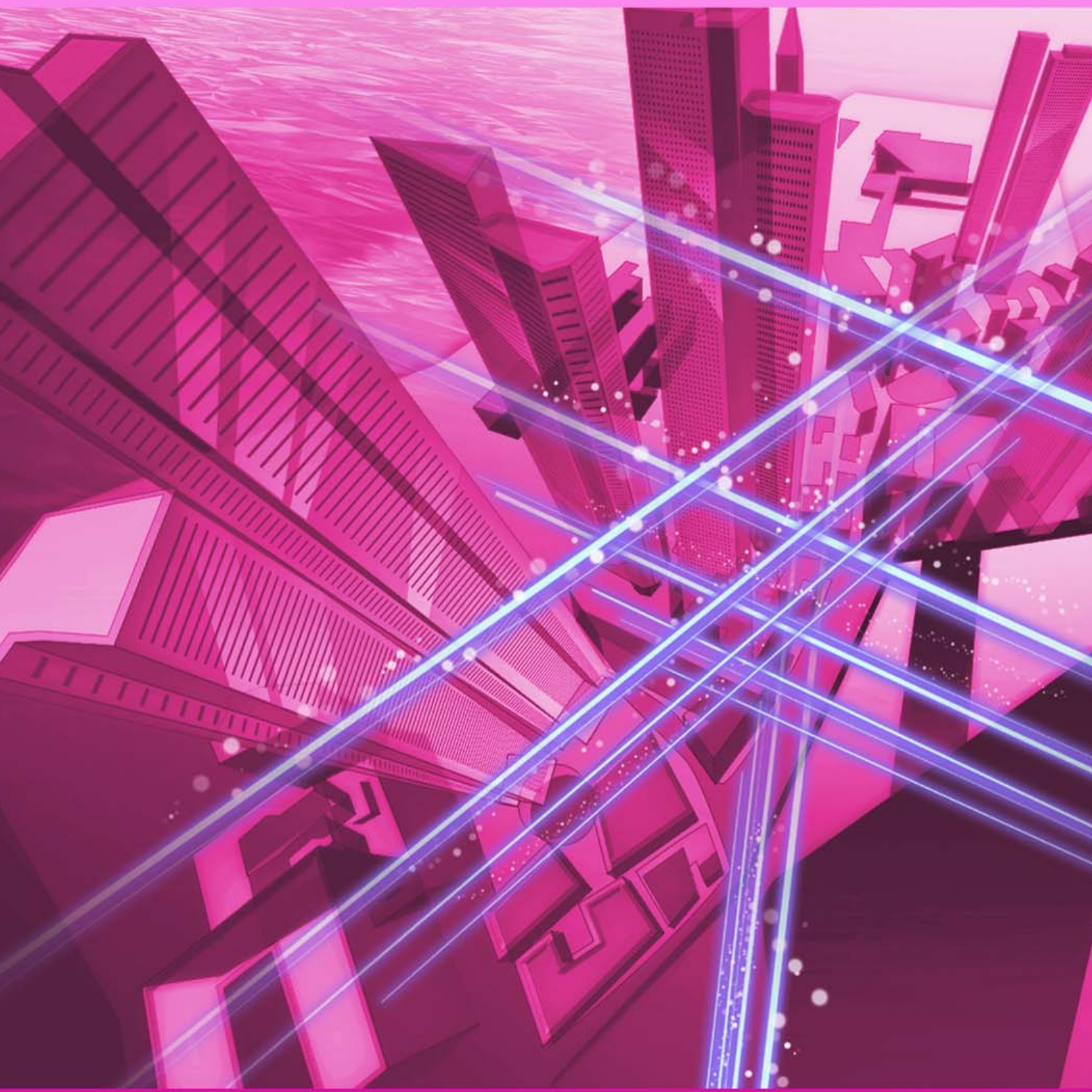

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No Wow, No Life. Creating a Society in Which People Can Feel Happiness and Have Exciting Experiences

Takaaki Sato
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Abstract

As a leader in the global mobile communications scene, NTT DOCOMO is pursuing coexistence of artificial intelligence and humans, construction of sustainable networks, and development of innovative technologies. We spoke to Takaaki Sato, senior executive vice president of NTT DOCOMO, about the company's technology strategy for creating a new world of communication culture and outlook for technological development focused on 6G (the sixth-generation mobile communications system).

Keywords: 6G, artificial intelligence, well-being

Striving to create a well-being society in terms of both private and public life

—Could you tell us about NTT DOCOMO's technology strategy?

The vision of research and development (R&D) at NTT DOCOMO is to "contribute to society by enabling people to be in a state of well-being in both their private and public life and continue to experience such a well-being society." To achieve this vision, we aim to (i) create a society in which individuals play a central role and can feel happiness and have exciting (wow) experiences and (ii) improve the productivity of individuals and society, while striving to develop customer-driven technologies that support business growth and create new businesses and technologies that will create value for the future.

Regarding the first aim, we intend to create a society in which people are free from various constraints and can participate in activities and communities according to their interests so that they can be in a state of well-being in both private and public life and continue to experience such a society.

One easy-to-understand example of this aim is the use of virtual reality (VR) technology and augmented reality (AR) technology to enable people to participate in events held in remote locations or experience live performances of their favorite artists in an immersive way at their homes. Another example is creating a service in which artificial intelligence (AI) will suggest information and communities that match interests and concerns of individuals to help them find a way of life that suits them.

Regarding the second aim, we intend to use technologies such as AI, including generative AI, to

improve people's work efficiency and increase their free time in a manner that improves the quality of life of individuals and the productivity of society as a whole. For example, by using AI to automate document creation and customer support, people will be able to focus on more creative work and generate new value. AI will continue to evolve in a way that gives rise to new services that will further enrich people's lives. NTT DOCOMO will work toward making this future a reality.

—How are you advancing technological development under the vision of creating happiness for society and individuals?

Although many people think we only deal with mobile communications, we are also researching and developing a wide range of services that enrich the lives of our customers. By using a wealth of customer data, including more than 100 million members of our customer loyalty program "d POINT CLUB," and real-time data, and conducting advanced data analysis using AI, we are addressing social issues, streamlining internal operations, improving the quality of the services we provide, and implementing marketing automation.

We also aim to resolve the labor shortage by enabling new work styles that go beyond the constraints of location and environment through the use of extended reality (XR), robotics, video big data, and other technologies. The metaverse and the Human Augmentation Platform—through which sensations, motions, and personal skills can be shared—will remove various constraints and expand the field of activity in which each individual can thrive.

We are also attempting to apply technologies for understanding customers and behavioral change to the digital medicine and healthcare fields to help people improve their lifestyles for better health. To ensure safer communication, we are investigating whether we can address emerging issues by using device technology preventing fakes and private cross-aggregation technology.

Some of these technologies can immediately contribute to addressing current business issues, while others are expected to be put into practical use 10 years from now. Nevertheless, we will not just develop technology but create new services that enrich people's lives by harnessing cutting-edge technology for achieving our vision of creating happiness for society and individuals.

Emphasizing the 3Ps: Platform, Process, and People

—NTT DOMOMO's R&D is involved in a wide range of technological developments. Could you tell us about your efforts to materialize the sixth-generation mobile communications system (6G)?

Stakeholders around the world are currently discussing the significance of promoting 6G.

Standardization work on 6G by the 3rd Generation Partnership Project (3GPP) began in August 2024, and in preparation for this work, NTT DOCOMO has been leading discussions with major global vendors for about a year. To consider values to be delivered with 6G, we must address challenges facing 5G.

For 5G, it is a global trend that telecommunications businesses that simply provide network connectivity are facing the challenge of declining profitability; in particular, it is difficult to secure profits from investments in network infrastructure. In light of this challenge, we believe it is necessary to (i) ensure economic efficiency by improving efficiency of the construction and operation of networks, (ii) enhance communications functions that are compatible with higher-level services and increase their value, and (iii) take measures to reduce electricity consumption for enhancing sustainability. To address these challenges, we are promoting 6G, focusing on the following five values.

(1) Sustainability

NTT DOCOMO Group declared in 2021 its goal to achieve carbon neutrality in its operations by 2030. It then expanded its target for reduction of greenhouse-gas emissions to include its entire supply chain with the goal to achieve net-zero greenhouse-gas emissions by 2040. Under the slogan "Changing the Environment with You," we aim for carbon neutrality in regard to our own greenhouse-gas emissions (Scopes 1 and 2) by 2030 and net-zero greenhouse-gas emissions, including those of its supply chain (Scope 3), by 2040. To achieve these goals, we will deploy IOWN (Innovative Optical and Wireless Network) photonics-electronics convergence technology by 2030 and promote faster communications and energy savings by developing technologies that contribute to reducing greenhouse-gas emissions from next-generation networks and information-processing infrastructure.

(2) Efficiency

To reduce costs by streamlining systems and operations, the overall design of 6G will be simpler than that of 5G, and AI will be proactively used to automate design and operation and maintenance of networks and optimize network configurations.

(3) Customer experience

Mobile networks have now become the fourth infrastructure that is indispensable to our lives in addition to electricity, gas, and water. To improve the reliability of networks as social infrastructure, we are investigating building networks with high fault tolerance. We are also attempting to (i) create digital twins through spatial computing using highly accurate positioning at the centimeter level and (ii) build the Human Augmentation Platform that can transmit and reproduce the five human senses anywhere using ultra-low-latency 6G communications.

(4) Network for AI

This involves the development of a network dedicated to AI. We intend to evolve the network from the one for use cases targeting humans to the one capable of leveraging AI, robots, and autonomous machines and create new revenue sources. We will provide computing resources and collect large amounts of data to maximize the value of AI while also further improving speed, capacity, and reliability and lowering latency.

(5) Connectivity everywhere

We will construct a network that connects anywhere, anytime. We are leading the world in expanding network coverage with direct access (DA) to smartphones through the best mix of LEO (low-Earth-orbit) satellites, GEO (geostationary-orbit) satellites, and HAPS (high-altitude platform stations).

—Could you also tell us your thoughts on your network strategy?

The widespread use of smartphones and the sudden increase in data traffic resulting from the use of social media and video viewing have placed a high load on our network and inconvenienced customers, particularly in urban areas in ways such as their smartphones are frequently disconnecting with the network. We are working hard to improve communication quality in these areas.

I believe that the "three Ps"—Platform, Process, and People—are the key factors that affect a network. First, Platform. Completion of introducing infrastructure or services does not mean the completion of our task. Rather, our task starts when customers begin using the infrastructure and services we provide through our platform. It is important to listen carefully to how customers feel, understand what issues they are facing, and quickly implement improvements to meet their expectations. Similarly, when it comes to Process, even if previously used technologies or processes were valuable at the time, they may have become obsolete with time, technology evolves, and society's values change. Therefore, we need to constantly think about and update what the optimal process is to provide the value desired by our customers. To this end, we are discussing with people outside the company to keep up with trends and gain new insights and striving to improve our technology. Lastly, People. It is important for us to take external criticism seriously so that we can see ourselves objectively and make improvements. Viewed from the outside, NTT DOCOMO may differ from other carriers in many ways, such as having stricter standards than other carriers. We may not notice our negative or positive points if we stay confined to our workplace. I believe we need to be open to criticism from outside and sincerely acknowledge it and respond accordingly. At NTT DOCOMO, we should be naturally able to do what other companies can do, remove our own constraints, and focus on highlighting our advantages.

In response to increasing data traffic, we are taking extensive and intensive measures in more than 2000 service areas nationwide to meet the current and near-future traffic demand. Specifically, we are implementing a combination of "point"-based measures and "line"-based measures, with the latter aimed at ensuring that customers can use our services without inconvenience inside trains and station areas while traveling.

With an eye on future demand growth, we have made an upfront investment of 30 billion yen. The areas where we are implementing intensive measures include train stations, downtown areas, and residential areas. For areas along nationwide railway routes, such as JR, private railways, and subways with large

numbers of passengers, we are currently working hard to utilize existing base stations (by adjusting angles, directions, and levels of their radio-wave emissions), further improve the quality of 5G uplink channels, take measures for base-station equipment, add and install 5G/4G equipment, and deploy advanced massive MIMO (multiple-input multiple-output) equipment (large-capacity, high-speed wireless communications equipment).

While anticipating various usage patterns of our customers, we are committed to improving communication quality so that they can use our services without any inconvenience.

Enrich your life by stepping out of your comfort zone

—You consistently think about technological development from the customer's perspective. Looking back on your career so far, what made you think that way?

After graduating from university, where I majored in civil engineering, I joined NTT in 1990. I thought I would be obviously assigned to departments related to civil engineering; however, during my training as a new employee, I was recruited by and assigned to the Mobile Communications Department, regardless of the fact that I didn't know the slightest thing about wireless technology. At first, I was often baffled, but I eventually came to view my situation positively through the mindset that not knowing anything is a weapon because my ignorance allows me to see things from various perspectives without preconceptions. On the basis of that experience, I tell employees who are anxious about being transferred that change is an opportunity and that they can facilitate innovation in the new department because they have viewpoints that are not possessed by others in that department.

I have previously been involved in field operations for three years as the head of the Hokuriku Regional Office of NTT DOCOMO. During that time, I realized that although there were many issues in the field, people in the field did not have the necessary means to address them. I also realized that although R&D members had developed a variety of technologies and produced research findings, they had not sufficiently examined where such technologies should be applied in the field.

I therefore set up monthly meetings—attended by both field workers and members from R&D departments and also by myself—for the purpose of matching the needs of both parties and creating a mutually beneficial cycle. On the basis of that experience, I now encourage R&D members to go out into the field, spend a month or so learning about the issues there, and play a role in connecting those issues to the technology and results back at R&D.

Our R&D organization hires mid-career people with various backgrounds. By leveraging the experience in the field, knowledge, and expertise acquired in their previous jobs, they are creating a chemical reaction that acts as a bridge between issues in the field and technologies developed by R&D.

—Would you tell us what you value as a top executive?

"No wow, no life" is my valued motto, the essence of which is incorporated into our R&D vision. That is, for as long as I live, I want to spend each day, feeling a sense of wow. Without excitement, life would be tasteless even if I live a long life. I also want to work hard so that everyone and our families and friends can live happy lives that make them feel "wow."

I also cherish the phrase, "Step out of your comfort zone." When stepping out of your comfort zone, you may feel anxious and scared at first. But you will gradually become more comfortable with the new environment and the people and things there. At the same time, you will build many new relationships. I believe that if we have the courage to repeatedly step out, we will be able to enrich our life.

Finally, I want to encourage all employees to clearly define their aspirations for their work and keep working toward achieving them. Many employees of the NTT Group are working on similar or related tasks to those of our employees. Right now, they may not know each other, but in my position as senior executive vice president, I want to make it easy for them to build relationships in the future. I also hope to create wow experiences together with partners who share the same aspirations. I look forward to working with you.

Interviewee profile

■ Career highlights

Takaaki Sato joined Nippon Telegraph and Telephone Corporation in 1990. In his career at NTT DOCOMO, he was appointed Senior Manager of the Radio Access Network Engineering Department in 2005, General Manager of the Service Design Department in 2016, General Manager of the Service Innovation Department in 2019, Senior Vice President and Executive General Manager of the Hokuriku Regional Office in 2020, and Executive Vice President and Executive General Manager of the R&D Innovation Division in 2023. He has been in his current position since June 2024.

Approaching Quantum Error Correction Using Bosonic Qubits While Looking Beyond the Red Ocean of a Research Field

Shiro Saito
Senior Distinguished Researcher,
NTT Basic Research Laboratories

Abstract

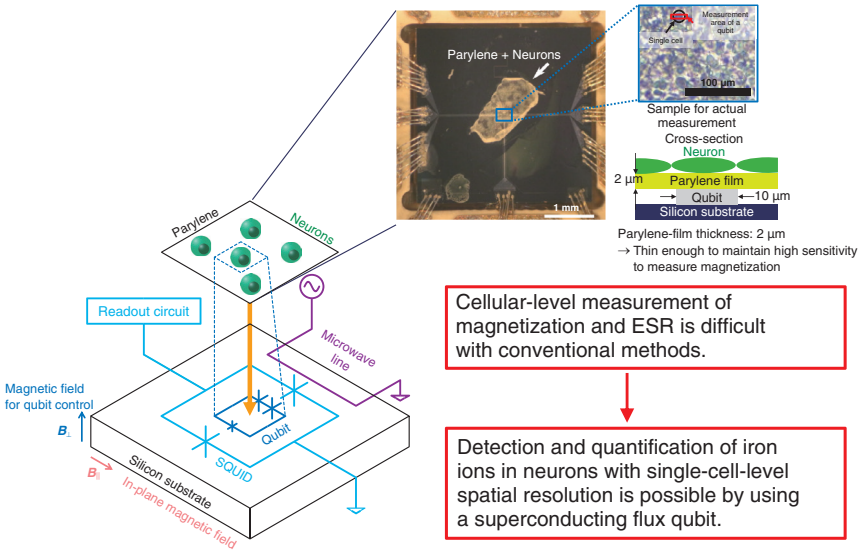
A challenge with a superconducting quantum bit (qubit)—the basic element of a quantum computer—is its short lifetime. To overcome this challenge for developing a quantum computer, approaches, such as elucidating the mechanisms that affect the lifetime of a qubit and extending its lifetime by correcting errors that occur when it reaches the end of its life, have been taken. Extending the lifetime of a qubit is expected to improve the accuracy of quantum sensing. A superconducting flux qubit has two quantum states, which correspond to the direction of the superconducting current, and by controlling these states with a magnetic field, the qubit can be used as a highly sensitive magnetometer. We interviewed Shiro Saito, a senior distinguished researcher at NTT Basic Research Laboratories, who aims to apply a hybrid combination of high-performance magnetometers and biological samples to pathological diagnosis. He talked about the detection of iron ions in neurons by using superconducting flux qubits and shared his research approach that looks beyond the red ocean of a research field.

Keywords: superconducting flux qubit, two-level-system defect, bosonic qubit

Clarifying the mechanisms behind the characteristics of a superconducting quantum bit through experiments and progressing toward its application

—Would you tell us about the research you are currently conducting?

Our group is researching superconducting quantum bits (qubits), focusing on three themes: "detecting iron ions in neurons by using superconducting flux qubits," "detecting and identifying defects that limit the lifetime of superconducting qubits," and "studying superconducting bosonic qubits." As a fundamental element of a quantum computer, a superconducting qubit exploits quantum states that emerge in a superconducting environment. Among the several types of superconducting qubits, a superconducting flux qubit is a superconducting circuit consisting of a superconducting loop. The qubit can be controlled by



SQUID: superconducting quantum interference device

Fig. 1. Experimental setup for detecting electron spins in neurons by measuring the spectrum shift of a qubit.

the magnetic field penetrating the loop and functions as a highly sensitive magnetometer. In my previous interview (November 2021 issue), I explained that we have demonstrated electron-spin resonance (ESR) by using this magnetometer to detect electron spins, which have the properties of a tiny magnet, and developed an ESR method based on this principle for analyzing material samples containing a small number of electron spins in a small volume.

For our first theme, "detecting iron ions in neurons by using superconducting flux qubits," when conventional measurement methods are used, for example, when electron spins of cells in the brain are measured by biopsy, only the average value of the spins of all cells can be measured. In contrast, sensors using superconducting flux qubits achieve high spatial resolution, which enables us to detect the property of electron spins of individual cells. We began research on the detection of iron, which is the most-abundant trace metallic element in the human body. We chose iron because knowing the redox state of iron is key to understanding oxygen transport and the electron-transport chain. Iron also plays an important role from a pathological perspective, for example, the deposition of iron in cells is related to diseases such as Alzheimer's disease. In an experiment, we attached a biological sample of neurons cultured on parylene (i.e., a paraxylylene polymer with a linear crystal structure) to a chip consisting of a superconducting flux qubit and measured the spectrum of the superconducting flux qubit to detect the electron spins in the neurons (**Fig. 1**).

The magnetic field generated by the electron spins changes to reflect the difference in the orientation of the electron spins in the biological sample, which are disoriented at high temperatures but aligned at low temperatures. By detecting the change in the magnetic field in the form of a shift in the spectrum (**Fig. 2**), we succeeded in detecting the electron spins caused by the iron ions contained in the neurons at single-cell-level spatial resolution.

These results indicate that detection of electron spins using superconducting flux qubits is highly sensitive and has the advantage that even small amounts of sample can be detected. I therefore believe that it can be applied to pathological diagnosis or to the measurement of extremely valuable samples such as milligram-sized samples of sand collected from the asteroid Itokawa. Going forward, we intend to obtain spectra by using the ESR method and from those spectra, identify which ions an electron spin is caused by, for example, iron or copper ions.

Conducted in collaboration with Shizuoka University, this research was partly supported by the Japan Science and Technology Agency (JST) as a research project "Quantum sensing using superconducting flux qubits" (Research Director: Shiro Saito)" (No. JPMJCR1774) in the Core Research for Evolutional

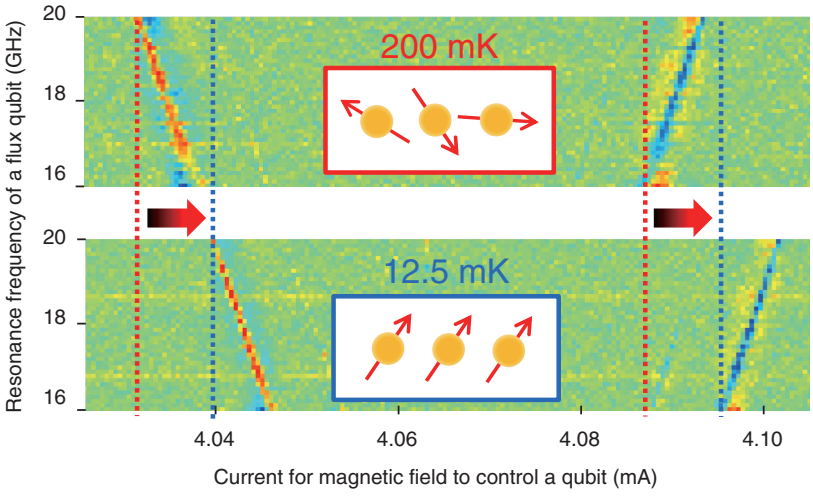


Fig. 2. Spectrum of a qubit.

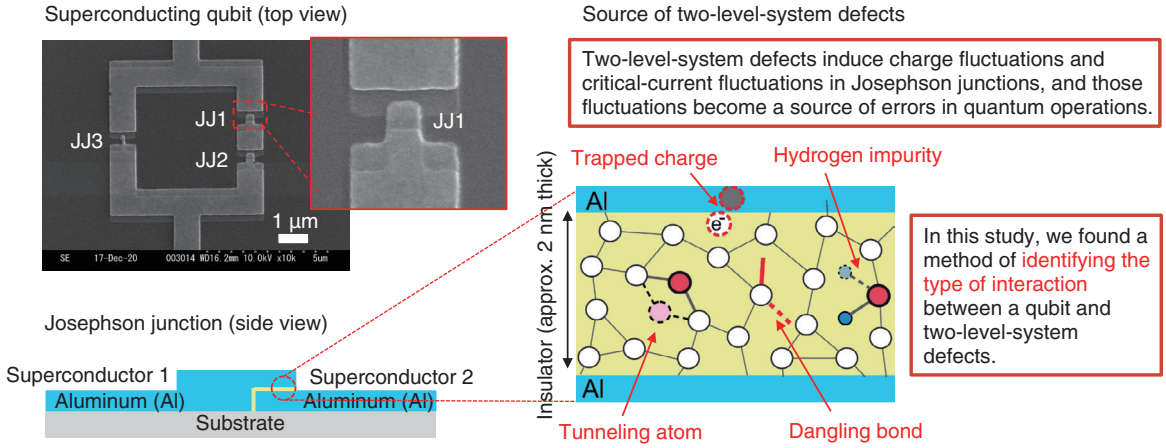


Fig. 3. Two-level-system defects.

Science and Technology (CREST) program "Creation of Innovative Quantum Technology Platform Based on Advanced Control of Quantum States" (Research Supervisor: Yasuhiko Arakawa) and was published in the British scientific journal *Communications Physics* on February 6, 2023.

—What kind of research is "detecting and identifying defects that limit the lifetime of superconducting qubits"?

It is a research theme to extend the short lifetime of qubits by detecting and identifying defects that limit the lifetime. In the aforementioned research on electron-spin sensing using a superconducting flux qubit, we attempted to narrow the linewidth of the qubit's spectrum by extending the lifetime of the qubit to improve sensing sensitivity. However, while sensing electron spins, we discovered a phenomenon that slightly differed from what we expected and began investigating it as a separate theme.

A major noise source that limits the lifetime of qubits is two-level-system defects that cause charge fluctuations in the Josephson junction contained in the qubit (**Fig. 3**). The superconducting loop of a superconducting flux qubit contains three Josephson junctions (JJ1 to 3 in the figure), and as shown in the enlarged view of JJ1, each Josephson junction is

composed of two superconductors joined via an insulating film. If the insulating film is grown epitaxially, and the atoms are regularly aligned, the Josephson junction will be free of defects, and the qubit will have a very long lifetime; however, an aluminum-oxide insulating film is currently grown in an amorphous state in which atoms are irregularly aligned. Trapped charges, atomic tunneling, and dangling bonds are considered the causes of two-level-system defects. Although well-known studies have attempted to theoretically explain two-level-system defects, and the existence of two-level-system defects is clear, it is currently impossible to prevent them.

There are two main types of interaction between superconducting qubits and two-level-system defects: charge and critical current. For a charge-type interaction, charge fluctuations of a two-level-system defect displace the charge in the Josephson junction, thus coupling the two-level-system defect to the qubit. For a critical-current-type interaction, charge fluctuations of a two-level-system defect cause a change in the critical current in the Josephson junction, thus coupling the two-level-system defect to the qubit. A charge-type-interaction two-level-system defect is detected when there is a resonance transfer between a single excitation of a qubit and a single excitation of a two-level-system defect. On the contrary, a critical-current-type-interaction two-level-system defect is detected when there is a resonance transfer between two excitations of the qubit and one excitation of the two-level-system defect. By finding the differences between these detection conditions through experiments, it has become possible to distinguish between the two types of interaction between superconducting qubits and two-level-system defects.

By measuring the spectrum of two-level-system defects while controlling the transition frequency of superconducting qubits, we succeeded in visualizing the difference between the two types of interaction between a qubit and a two-level-system defect on the spectrum. Therefore, it has become possible to distinguish between the two types of two-level-system defects by sweeping the transition frequency of a qubit.

By advancing this research, we intend to elucidate the properties of defects in superconducting qubits, the result of which will provide feedback for the sample-fabrication process to optimize the fabrication process and materials and create defect-free, long-lifetime superconducting qubits. As a short-term application, it became possible to model noise due to two-level-system defects, which can be applied to the optimization of gate operations of qubits, improving the performance of currently available quantum computers.

This research was partly supported by the following research and development (R&D) projects: "Quantum sensing using superconducting flux qubits" (Research Director: Shiro Saito)" (No. JPMJCR1774) in the CREST program "Creation of Innovative Quantum Technology Platform Based on Advanced Control of Quantum States" (Research Supervisor: Yasuhiko Arakawa) as well as "Research and development of bosonic codes using superconducting resonators" (Performer: Shiro Saito) (No. JPMJMS2067) in the "Development of Integration Technologies for Superconducting Quantum Circuits" (Project Manager: Tsuyoshi Yamamoto) project, which is the national Moonshot R&D Program Goal 6: Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050 (Program Director: Masahiro Kitagawa) promoted by JST. The above result of this research was published online in the American Scientific Journal *PRX Quantum* on December 21, 2022.

—You recently started investigating superconducting bosonic qubits, right?

Our third theme, "studying superconducting bosonic qubits" was started as the aforementioned research topic "Research and development of bosonic codes using superconducting resonators" (Performer: Shiro Saito) (No. JPMJMS2067), and we have obtained new results.

One of the most important applications of superconducting quantum circuits is quantum computers. To improve the performance of a quantum computer, it is necessary to increase the number of qubits that it uses; thus far, a quantum computer with up to around 1000 qubits has been achieved. A qubit has a short lifetime, and external disturbances can change its state and cause errors. To ensure the operation of a quantum computer, quantum errors must be corrected. The currently mainstream error-correction method implements a surface code using qubits called "transmons" in a manner that increases the number of qubits so that their redundancy can be used for error correction. In the case of a typical error rate of 0.1%, about 1000 physical qubits per logical bit are needed to correct errors; in other words, 1 to 100 million qubits are needed for a meaningful quantum computation

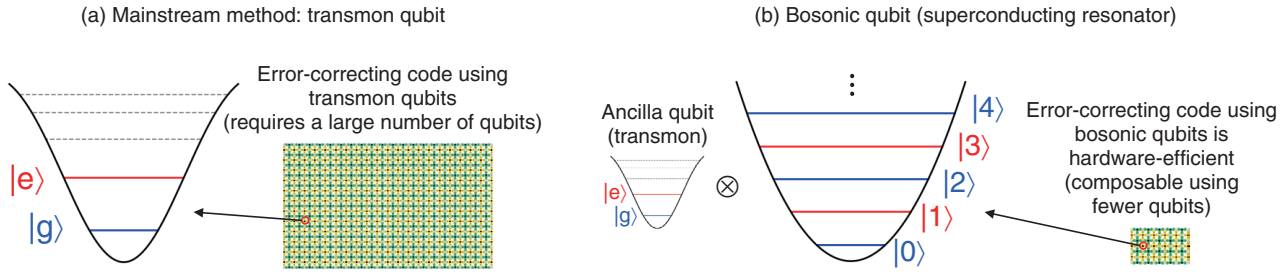


Fig. 4. Hardware-efficient bosonic qubit.

(**Fig. 4(a)**).

In contrast, a bosonic qubit is created by combining a storage cavity called a resonator and ancilla qubit (transmon) to form a single qubit, and errors are corrected by the redundancy and degrees of freedom of the theoretically infinite number of energy levels within the resonator (**Fig. 4(b)**). Compared with the conventional error-correction method using transmon qubits, the method using bosonic qubits requires fewer qubits (so less hardware) by one to two orders of magnitude. However, bosonic qubits have many energy levels, so it is extremely difficult to control them. Therefore, controlling quantum states in those energy levels is a challenge with bosonic qubits.

Thus far, we have prototyped a three-dimensional coaxial cavity made of aluminum and achieved a Q value (an index that represents the quality of a resonant circuit in terms of the low level of its loss) of over 10^8, which is equal to or better than that achieved in previous research. We have also optimized the design of the bosonic qubit and improved the properties of the ancilla qubit, creating an environment in which bosonic qubits can be implemented. As a first step of this research theme, we have successfully observed the spectral splitting of ancilla qubits in accordance with the photon number states in the storage cavity.

We are beginning to see results such as the encoding of bosonic codes. By refining technology of these results, we intend to implement binomial codes in the resonator and, in parallel, build a prototype niobium resonator to achieve an even higher Q value.

Looking beyond the red ocean of a research field and cherishing human connections

—What do you keep in mind as a researcher?

Research on superconducting quantum computers is a "red ocean," where a growing number of researchers are actively investigating it. At its core, mainstream research in related technologies is conducted by researchers supported by global corporations or national governments with a wealth of resources. Facing an overwhelming difference in resources, we would find it extremely difficult to compete with them head on. Accordingly, I'm trying to take a slightly different approach from those researchers by looking ahead to the future, i.e., targeting research areas that are still new, interesting, and promising and have the potential to turn the tables in the future such as bosonic qubits. In my previous interview, I talked about analyzing the current situation and selecting a theme that would enable me to use my strengths to create novelty, and I have been updating this approach.

Regarding the two-level-system defects that I mentioned, our initial goal was to increase the spin sensitivity to enable us to detect electron spins; however, we were unable to detect electron spins due to insufficient sensitivity but detected an unexpected phenomenon. At that time, a postdoctoral researcher and I thought about what we could detect with our method and found that we could detect two-level-system defects at high frequencies. Using one of our strengths, namely, a variable-frequency superconducting flux qubit to measure the spectrum of two-level-system defects, we also discovered two spectra: a spectrum with the same shape as the qubit and spectrum with a shape twice the frequency of the qubit. We then went back to the starting point and calculated the Hamiltonian of the qubit coupled with two-level-system defects and were able to detect and identify the types of the defects. I believe that even when the results differed from what we expected, pursuing our goal while changing our perspective and digging deeper led to new discoveries.

After I presented these results during an invited talk

at a conference called "Superconducting Qubits and Algorithms," a researcher working on the theory of two-level-system defects approached me and said he was highly impressed by our results because he had been repeatedly conducting experiments to distinguish between the two types of two-level-system defects but could not produce results. I'm delighted that the efforts we've been making have led to these results and that opportunities for future collaboration and joint research were created, which will be valuable when this research progresses further and we need theoretical support.

—What is your message for younger researchers?

I hope you will cherish your connections with others. In detecting iron ions in neurons by using superconducting flux qubits, we were able to achieve results by combining superconducting qubits with biological samples. NTT Basic Research Laboratories has recently produced a variety of achievements through hybrid combinations of different fields such as mechatronics and photonics. These achievements are the result of collaborations between professional researchers by harnessing human connections. If we look beyond NTT, we will find many excellent professors at universities and other institutions in Japan who are researching topics that NTT does not handle. If we keep our eyes open and find teams with which we could conduct collaborative research, or if we look overseas, the opportunities will be even greater. To take advantage of such opportunities and expand your research, it is important to build connections with those researchers.

I also think you should be proactive and challenge yourself in everything you do. For example, it might be a good idea to try your hand at large projects such as the Moonshot programs or JST's CREST. Although the application process for these projects is time-consuming, it helps you clarify the purpose and plan of your research, and if your proposal is accepted, it will attract people to the project. It is thus a good opportunity to make connections.

Finally, I encourage you to participate in research abroad, because you will be exposed to research cultures that differ from that of Japan and will also be able to make connections with outstanding international researchers.

■ **Interviewee profile**

Shiro Saito received a B.E., M.E., and Dr. Eng. in applied physics from the University of Tokyo in 1995, 1997, and 2000. He joined NTT Basic Research Laboratories in 2000. Since then he has been engaged in quantum information processing using superconducting circuits. He was appointed as distinguished researcher of NTT in 2012 and senior distinguished researcher in 2021. He was a guest researcher at Delft University of Technology from 2005 to 2006. He was a guest associate professor at Tokyo University of Science from 2012 to 2020 and promoted to a guest professor in 2020. He is a member of the Physical Society of Japan and the Japan Society of Applied Physics.

Communication Support to Deepen Human Connections Leading to a Spiritually Enriched Society through Information Technology

Naomi Yamashita
Distinguished Researcher, NTT Communication Science Laboratories

Abstract

While information technology enriches our lives, those of us who use it are also required to develop literacy in it and understand its pros and cons. For example, artificial intelligence (AI) is advancing day by day, and AI-human communication is even becoming easier, but we must be careful because this could also lead to a decline in human-to-human communication. NTT Distinguished Researcher Naomi Yamashita is working to deepen communication using information technology. For this issue, we spoke to her about her research into solving the various problems facing modern society and the mindset required of researchers.

Keywords: information technology, human-computer interaction, human connection

Using information technology to support people and create a positive cycle of human connection

—First of all, what exactly is "research on communication support to deepen human connections"?

In the "research on communication support to deepen human connections" project, we aim to use information technology to create opportunities for human-to-human communication and thereby resolve social issues. In the modern age, where information technology is widespread, we can easily communicate with people in remote locations, but at the same time, problems such as social fragmentation and isolation are becoming more apparent. For example, in recent years, we often hear people say that "it's easier to talk to artificial intelligence (AI) than to other people, and it makes life less stressful." However, I am concerned that if AI continues to evolve in this way, people will become truly isolated. It's true that human communication often leads to misunderstandings and conflict. But there are also concerns such as the potential to just brush off what you find annoying, or dying under the watchful eye of AI. "Society 5.0" sets out an ideal form of our future society. Its aim is for AI to become a presence that connects people well, rather than replacing people. It considers the direction of future AI evolution and methods for implementing it in society.

This research belongs to the field of human-computer

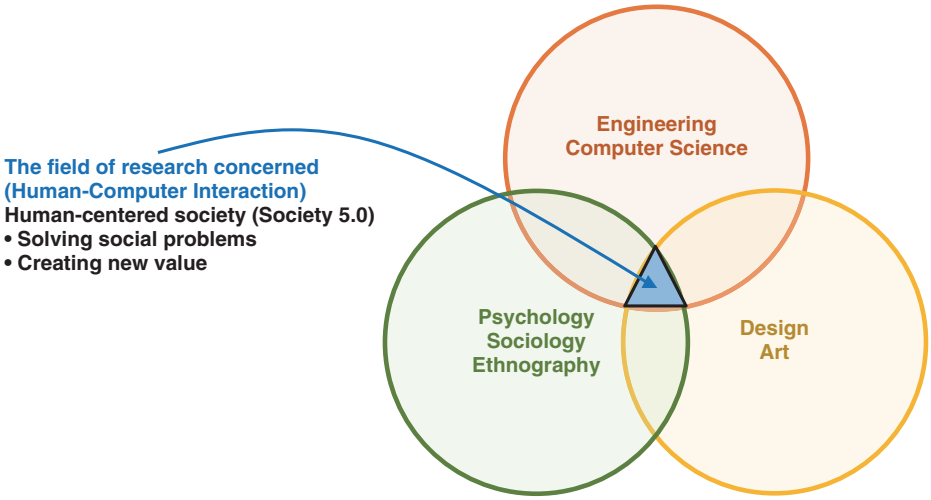


Fig. 1. Overview of the field of human-computer interaction.

interaction (**Fig. 1**). This field is a multidisciplinary domain that studies the relationship between people and various information technologies, including computers, and is characterized by the fact that many research fields overlap. For example, by combining perspectives, methods, and knowledge from computer science, cognitive science, psychology, sociology, as well as art and ethnography, we seek information technology that can be used to create new value to realize a more livable and prosperous society by taking a multifaceted approach to social issues.

One example of the work I have been involved in is research into supporting the social reintegration of people with depression. The reason I started this research was because I thought that as a specialist in designing information technology that connects people, I should return to the question of "what should be done?" and take on challenges that will contribute to solving social problems. I had heard about many of the social issues that the spread of information technology was causing when I went to give lectures. For example, mothers who are holding their babies used to make eye contact with their babies and talk to them, but nowadays, some mothers are so distracted by their smartphones that they are unable to make enough eye contact with their babies. In response to this, there have been concerns raised in fields such as cultural anthropology, and there have been cases where young animals who were not raised by their parents in zoos have grown up to neglect their own children in the same way. There is a fear that this could happen to humans too, as it becomes harder and harder to raise children in successive generations. My thinking on this issue is that if the negative cycle is really caused by the spread of information technology, then there is the potential to use information technology to create a positive cycle.

When I actually thought about it and considered it from my own surroundings, the one community that came to mind was people with depression. For example, when someone with depression takes some time off work and then returns to work, I often hear stories of how people don't know how to interact with them and end up treating them with excessive caution, and after a while the depression comes back. Of course, there are treatments for people with depression, but I had a couple of thoughts. One, if the environment around the patient doesn't change, the same thing will happen over and over again. Two, if you are going to intervene, you need to include not only the patient themselves, but also the people around them who are taking in the patient, otherwise the problem won't be solved. And it is information science, not medicine, that can step in such situations. The project was launched, and the app "Mimamo Mate" (**Fig. 2**), which was developed based on a series of studies, was used by a non-profit organization that assists with mental health.

—What difficulties did you encounter in your research?

I originally started my research in mathematical engineering when I was at university, so I thought I

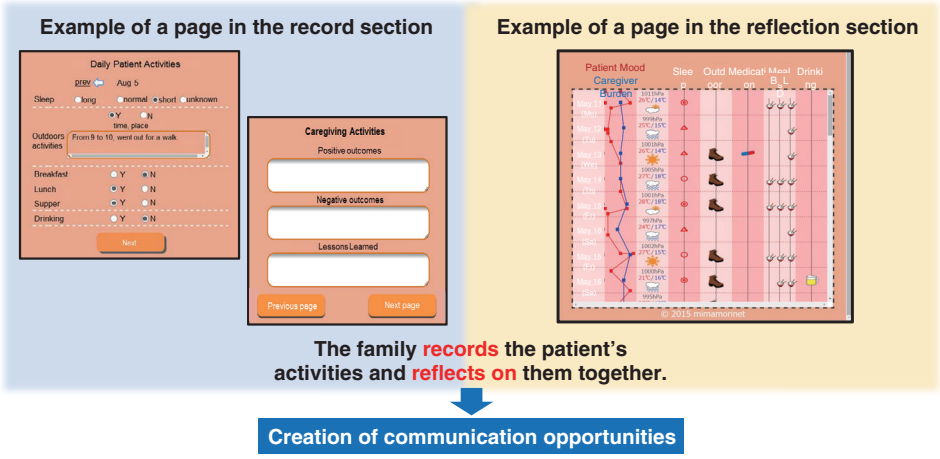


Fig. 2. Screen of the "Mimamo Mate" app.

would use mathematics as my weapon. However, I gradually began to feel that looking at data based on numbers alone had its limitations. So I changed my research direction and worked on joint research with many people to learn research and analysis methods based on the ideas of fields such as sociology and psychology. I thought that the advice and comments of experts in the medical field would be particularly important in advancing this research, so I actually asked them to join the project and work with us on the research.

More specifically, while previous research on depression support had focused on making treatment for patients more effective and efficient, this research focused on communication between patients with depression and their families, and we worked on building a system that would create opportunities for communication between them. The reason for this is that while it has been demonstrated that patients with depression are easily affected by their family environment, and that patients with cooperative family caregivers recover more quickly, there are almost no studies that focus on family caregivers or improving the family environment. Therefore, we thought that improving the family environment through family caregivers would improve the symptoms of patients with depression.

However, at the beginning of the project, we encountered many unexpected obstacles. For example, the initial approach involved conducting research by approaching the families of patients through our collaborating psychiatrist, but such research needed to be approved by the ethics committee of the medical school, and this took more than half a year. Furthermore, although we were finally able to approach family caregivers via doctors, since we had reached the family with the patient's permission through the doctor's referral, of course the family could not say anything if they were dissatisfied with the doctor or patient, so it was quite difficult to find out their worries and true feelings. Ultimately, we were able to create a situation where we could investigate what people really think quite freely by directly recruiting and interviewing family members without going through doctors and patients. As you can see, even just changing the method of recruitment can completely change what you can find out, and each process up to the point of producing research results was a continuous struggle, but we were able to reach the final development stage after receiving a lot of feedback.

—What other research are you involved in?

In addition to supporting people with depression, I have also been involved in research to solve current social problems by using information technology to support communication and collaboration. We have designed a number of systems based on user analysis to meet the needs of various stakeholders for a wide range of social issues, including supporting the participation of non-native speakers in communication between multinational members and supporting meetings and interactions for LGBT people. For example, we used a device (**Fig. 3**) that measures stress levels by attaching a sensor to the arm to help

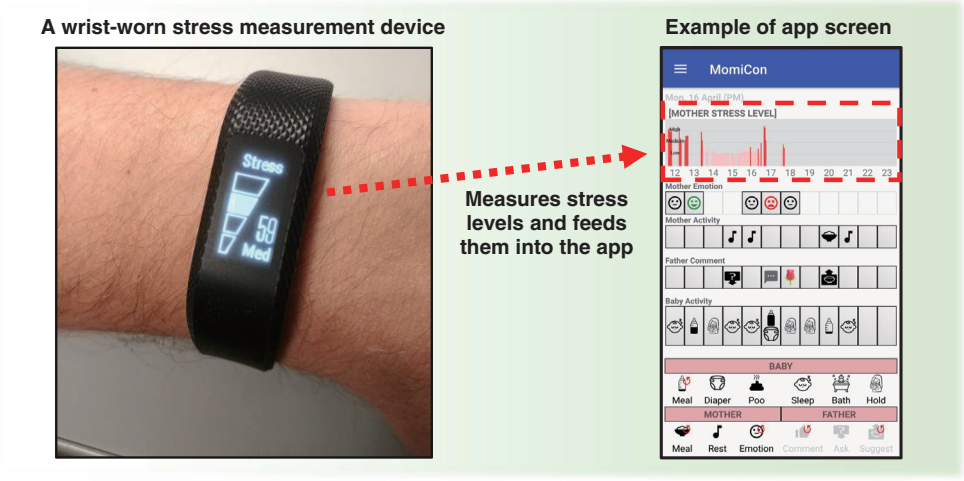


Fig. 3. Example of design based on social problems.

postpartum women deal with postpartum depression. More specifically, by using an app that shares the mother's stress levels (collected by sensors) with the father, we have succeeded in creating opportunities for communication between husband and wife.

The fine points of one's own emotions are where the clues to research are hidden

—What are your future research prospects?

While many of the studies I have worked on so far have been short-term, solving many of the social issues that society is facing, such as a declining birth-rate and aging population, environmental issues, and the prevention of lifestyle diseases, requires mindset and behavioral change from a long-term perspective. Moving forward, we will scale up our research even further and look towards research from a longer-term perspective. There is pressure on young researchers to keep producing results, so there is a risk involved in taking on a challenge that will take time to produce results, but I think that the research challenges I should be tackling now are precisely those that are considered difficult.

Looking further ahead, NTT's vision for IOWN (Innovative Optical and Wireless Network) is to value diversity and improve understanding between people with different values, as well as the quality of the "connections" between people and society, and I believe that this is in line with the direction of my research. As mentioned above, the rapid development of AI is raising expectations for improved convenience and risk avoidance through future predictions, but the way AI is used and its impact on users are also very important research topics. Moving forward, we will continue to strive to realize a more prosperous future society while exploring ways to provide these technologies.

In particular, the social issues we will be tackling are complex, and it is not feasible to solve them with a single field or technology. By combining diverse perspectives and knowledge with the help of as many people as possible, we hope to create deeper insights and practical solutions, and together achieve a sustainable and prosperous society.

—Finally, do you have a message for researchers, students, and business partners?

At NTT Communication Science Laboratories, where I work, we research information technology, people, and the connection between people and information technology, and the freedom to choose research topics is very appealing. At the same time, I think that some young researchers may be experiencing difficulty with having to do their best with their daily workload, and then also having to carry out research and produce results on top of that. In such cases, I think it is important to stop and reflect on what is being asked of you, and to have the courage to be prepared to let go of something. This does not mean that you should abandon things irresponsibly. I think that you can achieve your aim by suggesting something is unnecessary or asking for help from other people.

I also think it is important to pursue your own strong points and passions. The key to expressing your commitment and strengths is often to be found near-at-hand. The fine points of emotions that arise in everyday life are the things that reveal a person's values. For example, if you get angry, by asking yourself why you're angry, you can become aware of your hidden values, such as how you think something should be. And if you think about things from a big-picture perspective, asking yourself questions like "Is that really how it should be?" and "Will that really make for a better society?", I think you will be able to see the path you should take. I think it would have been tough for me to do that when I was younger, but I hope that this will be of some help to young researchers who are struggling to find their way in research.

■ **Interviewee profile**

In 2001, Naomi Yamashita completed a master's program in applied mathematics and physics at the Graduate School of Informatics, Kyoto University. In the same year, she joined Nippon Telegraph and Telephone Corporation. In 2006, she completed a doctoral program in social informatics at the Graduate School of Informatics, Kyoto University and obtained Doctor in Informatics. She is engaged in research on information technology to solve problems facing society (such as language and cultural friction issues associated with advancing globalization as well as mental health issues). In 2024, she was named a fellow of the Information Processing Society of Japan (IPSJ), in 2020 she received the KDDI Foundation Award, in 2016 she received the IPSJ Yamashita SIG Research Award, and in 2011 she received the IPSJ Nagao Special Researcher Award.

New Developments in Communication Science Research in the Generative AI Era—Exploring the Nature of Humans and Information for Co-creating Human-centered Technologies with AI

Futoshi Naya

Abstract

NTT Communication Science Laboratories (CS Labs) is dedicated to the advancement of "heart-to-heart communication" between humans and computer systems. Our research focuses on the development of fundamental theories that explore the nature of information and humans, as well as the creation of innovative technologies that will revolutionize society. This article highlights some of CS Labs' efforts toward the coexistence of humans and artificial intelligence (AI), taking into account the recent and rapidly advancing trend of generative AI.

Keywords: communication science, artificial intelligence, brain science

1. Introduction

The news that OpenAI has reached 100 million users in just two months since the release of ChatGPT, an interactive generative artificial intelligence (AI), in November 2022, has had a huge impact around the world. As the term "interactive" implies, it has the ability to interact naturally with humans. In addition to writing, summarizing, and translating natural sentences, it can also read and answer questions about charts and diagrams. Furthermore, it can automatically generate desired images, videos, music, and even programs based on user instructions. These capabilities are attracting significant interest. This is due to the significant improvement in the computational power of graphics processing units (GPUs), which has supported the development of deep learning, as well as a major breakthrough in natural language processing called "transformer," a technology that enables learning from a vast and diverse language resource. The Generative Pretrained Transformer (GPT) is a large language model (LLM) that is the result of learning a large amount of data, and the GPT is equipped with an interface that interacts with users, making it suitable not only for researchers and engineers but also for a wide range of general users by providing an environment that can be easily used with smartphones and other devices.

With improvements in accuracy and reliability, such generative AI is sure to permeate our daily lives in the future. The recently announced GPT-4o has attracted further attention for its ability to handle multimodal input-output responses, such as real-time spoken dialogue and questions while capturing and analyzing video from a smartphone camera. However, current generative AI requires users to verbally

provide detailed information about the situation through prompts, depending on the type of response they want. Although a multimodal LLM is of course multimodal, the LLM is built on the basis of linguistic information, and multimodal input information such as video and audio are tokenized and processed to fit the input format of the LLM. Even before humans are able to understand and speak, their brains process all types of sensory information to understand and remember things and concepts, and abstracted symbolic systems such as language are associated with these representations in the brain. In other words, the current multimodal LLM has the limitation of not being able to handle sensory information that cannot be captured by language. This is called the *Symbol Grounding Problem* [1] proposed by cognitive scientist Stevan Harnard in 1990, and it is a fundamental problem that asks whether AI can understand things represented by symbols expressed in language in the same way that humans do by associating real-world concepts and meanings. The current LLM has not yet reached the stage where it can recognize the preferences, feelings, intentions, knowledge, and beliefs of others through facial expressions, attitudes, and conversations, and respond to them in a thoughtful way, or respond based on its own personality and beliefs, as humans do. There remains major philosophical issue, the *Theory of Mind* [2], which asks whether AI can infer and understand the state of mind of others as humans do.

Since its establishment in 1991, NTT Communication Science Laboratories (CS Labs) has been conducting fundamental research to pioneer the field of communication science that connects information and humans, with the goal of "interdisciplinary elucidation of the mechanisms of human understanding" [3]. In the 33 years since its founding, CS Labs has continued to create new discoveries and innovative technologies based on a deep understanding of the nature of information and human beings. As research advances, we recognize the need for a broad approach that spans a variety of interdisciplinary fields, including computer science, engineering, neuroscience, psychology, social sciences, philosophy, medicine, biology, and even mathematics.

In this article, I present representative examples of our recent research activities at CS Labs, which is expanding its interdisciplinary research fields, from the four perspectives of "mastering the essence of information," "mastering the essence of human nature," "getting close to people and society," and "pursuing fundamental theories."

2. Mastering the essence of information

At CS Labs, we are conducting research on information processing technologies for all media that convey information in communication. The development of sensing technology has made it possible to visualize and convert previously unobservable phenomena into meaningful information. *Sound* is a very familiar part of our daily lives, but it is usually measured using microphones. Sound travels as waves through the air, and while microphones can measure sound at the point where they are placed, it is difficult to know in detail how sound is generated and how it travels through space. In recent research at CS Labs, we have used optical technology with laser beams and a high-speed camera to capture sound waves as moving images, creating a *sound visualization system* that can be used to measure the sound field [4]. The phase of the laser light is modulated in accordance with the coarseness and density of the sound as it passes through the sound field. Our technology images the sound field by interfering with a laser beam that is unmodulated by the original sound and measures the modulation by capturing the interfering light with a high-speed camera. However, the noise in the measurement is very large, so by combining simulation-generated sound field datasets with deep learning techniques, we trained the model by varying the number of sound sources and noise conditions to eliminate this noise and provide a clear visualization of the sound field. This technology is expected to have a wide range of applications, including not only the visualization of various sounds but also the design of acoustic devices that reproduce pleasant sounds and the analysis of noise sources. Instead of using microphones to measure sound vibrations, which have had large individual differences in accuracy, we expect the technology to develop into an ultra-precise sound pressure measurement technology that aims to become the next-generation standard based on physical quantities such as optical frequencies.

In addition to the sound and light mentioned above, we have recently been developing a technology that uses AI to infer information about the behavior of the heart muscle cells that are the source of the electrocardiogram (ECG) [5]. Although the rough correspondence between ECG waveforms and diseases has been elucidated in medicine, it has been difficult to estimate what is happening at the level of myocardial cells, which is the basis of the ECG waveforms.

In this research, we developed a machine learning technique to solve the inverse problem of accurately estimating parameters generated from artificially generated ECG waveforms using the *Fugaku* supercomputer, which simulates a physical model of the heart and generates ECG waveforms using parameters such as Na (sodium) and Ca (calcium) ions in heart muscle cells, conductivity, and heart geometry as inputs. This research aims to create a bio-digital twin that enables the simulation of tailor-made medicine by measuring various biological data, including ECGs, and analyzing the factors and relationships among them to predict health conditions that reflect individual genetic characteristics and lifestyle habits and verify which drugs and treatments are effective. It is extremely difficult to model the heart as an organ, the relationships between blood and other organs from the microscopic behavior of heart muscle cells and biochemical reactions in the body, and also to model the macroscopic behavior of the entire human body as an individual. To solve this problem, it is necessary not only to capture the various events that occur in the body but also to have a technology that can quickly find accurate information from a large number of combinations about which events are interdependent and causally related to each other. The article in this issue introduces large-scale data analysis with high speed and rigor as a springboard for solving such problems [6].

3. Mastering the essence of human nature

CS Labs promotes research on the human senses (vision, hearing, touch, etc.), motor control, and emotions with the goal of scientifically elucidating the mechanisms of human information processing. We conduct a wide range of research, including studies that investigate the *universality* of human sensory, motor, and emotional functions, as well as research that seeks answers to fundamental questions about the *diversity* of innate characteristics of each individual and acquired experience and learning.

For example, it is known that when we walk, we unconsciously estimate our walking speed based on the information we receive from our eyes and adjust our walking motion to walk at the optimal speed. We have conducted research to determine whether the sense of speed we feel when we watch a first-person camera image of another person riding a bicycle on television is the same as the sense of speed we would feel when we were actually riding a bicycle. We experimentally investigated the change in walking speed of participants wearing a head-mounted display as they walked through a virtual corridor, moving the striped walls back and forth. The results indicated that the coarser the stripes, the faster the participants felt they were walking, and the finer the stripes, the slower they felt they were walking. However, when the participants did not walk but simply watched the stripes flow, the finer the stripes, the faster they felt they were moving, and the coarser the stripes, the slower they felt they were moving [7].

This suggests the possibility that the process of speed estimation in the human brain differs between motion and perception (multiple speedometers exist in the brain). This finding may contribute to the design of interfaces that provide highly immersive experiences in virtual spaces such as the Metaverse or present visual images that do not cause virtual-reality sickness.

The above is an example of research on the universality of human sensory and motor abilities. A familiar example of the diversity of human abilities is the dominant hand and foot. Many people develop differences in the dexterity of their hands and feet as they grow up. Right-handed people have great difficulty writing with their left hand, while people who have been corrected from left-handed to right-handed can move both hands with some dexterity, depending on the type of movement. Recent research at CS Labs has developed a method for easily measuring and quantitatively evaluating limb dexterity by simply rotating a smartphone in a circular motion. Experimental results indicated that the dominant hand has less variability in repetitive movements than the non-dominant hand, how this variability changes with age, and the essential mechanism by which this variability occurs. The article in this issue explains the above in detail [8].

Humans are emotional creatures, and their subjective evaluations of their impressions of things and others are subject to ambiguity, depending on their own physical and psychological state at the time. Questionnaires that ask about subjective impressions involve the individual's habitual emotional expressions and perceptions, fluctuating responses to the same question, and other ambiguities. Such uncertainty is an inherent part of human nature, but is it possible to know a person's true feelings from the pattern of their responses? In a recent study, we proposed a method for estimating the reliability of responses by statistically extracting response patterns and eliminating ambiguities [9].

4. Getting close to people and society

Thus far, I have introduced research on the nature of information and human nature. In this section, I introduce our research on the nature of communication, which is to connect information and people or to connect people to each other and society through information.

Today, information and telecommunication networks are deeply embedded in our daily lives and support all societal activities. Failure of network infrastructures, not only due to natural disasters but also due to human error, can have devastating effects. Designing more robust and reliable networks requires reliability analysis to analyze the durability of components against failures and disasters and vulnerability analysis to identify which components need to be strengthened. However, even with only 50 network components, there are up to 1000 trillion combinations, and conventional techniques can only be applied with approximate analysis methods. To evaluate the reliability of network design on a realistic scale, rigorous solution methods without approximations are required. In an article in this issue, we introduce in detail the rigorous solution method for network analysis using a data structure called decision graph [10].

In human sciences, it has become possible to quantitatively evaluate indices such as unnaturalness and comfort that people perceive in images by mathematically modeling and simulating human visual information processing mechanisms using deep learning technology. The article in this issue presents a technology for automatically generating images with which people feel natural and comfortable on the basis of a model of human visual information processing [11].

As reported in a recent press release, we were the first to discover that the electroencephalogram (EEG) of e-sports players just before a fighting game match reveal patterns that are strongly related to subsequent victory or defeat [12]. Unlike machines, humans are not only physically skilled, but their performance in a game is also affected by *mental* factors such as extreme pressure and tension. This study revealed EEG patterns associated with strategic decision-making about how to respond to the opponent's moves, and EEG patterns associated with emotional control to remain unperturbed in the face of adversity. It was also shown that a machine learning model can predict whether the player will win or lose with about 80% probability on the basis of the EEG state immediately before the game. This suggests that there is an ideal brain state for competitive gaming. This fact may lead to a new mental training that approaches the ideal brain state not only for sports but also for people who need to cope with pressure and require high levels of skill and ability, such as doctors performing surgery and pilots who need to make accurate judgments and control their aircraft. The IOWN (Innovative Optical and Wireless Network) concept promoted by NTT aims to enable Digital Twin Computing for humans. The results of this research will lead to the realization of skill enhancement by digitizing the brain state of a skilled person and simulating the process of approaching that of a skilled person from the brain state of a trainee.

In childcare and education, it is important to study the development of social skills with others in addition to the development of language in infants. The closeness that young children feel toward others is the basis for friendships and is an important topic in developmental psychology. However, the traditional method of behavior observation by adults is very time consuming, and the purpose is easily revealed to young children. In a recent study at CS Labs, infants aged 3–6 years were asked to draw pictures of themselves and others, and it was found that the smaller the horizontal distance between the closest points between the drawn figures, the greater the intimacy the infants felt towards the others, and that these were significantly correlated [13]. We plan to develop this finding into an assistive technology that can quickly detect interpersonal problems such as isolation and bullying in today's society, where there are many situations where adult supervision is not sufficient and make people aware of the need to prevent such problems.

5. Pursuing fundamental theories

In October 2021, CS Labs established the Institute for Fundamental Mathematics (IFM) [14], an organization dedicated to researching the fundamental theories of modern mathematics, to accelerate long-term research and development and further strengthen the source of the "fountain of knowledge." As of July 2024, there are eight mathematicians working at the IFM. Mathematicians from different specialties, such as number theory, algebra, geometry, representation theory, analysis, and dynamical systems, cross and connect with each other to explore unknown mathematical truths and solve important unsolved problems. Its mission is to propose approaches using

modern mathematics to important problems in other interdisciplinary fields, such as physics, biology, and medicine, and to discover new mathematical objects. The September 2024 issue of NTT Technical Review [15] presents recent important research results and perspectives from members of the IFM.

6. Conclusion

In this article, I have presented representative examples of recent research from CS Labs. As technologies such as generative AI become more sophisticated, the importance of human-centered technologies, such as understanding the nature of each person's diversity and how to process and convey useful information according to individual characteristics, will become increasingly important. We will continue to develop other areas of research toward a future in which humans and computers can truly understand each other and in which humans and AI can work together to create a better society.

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Futoshi Naya

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He received a B.E. in electrical engineering, M.S. in computer science, and Ph.D. in engineering from Keio University, Kanagawa, in 1992, 1994, and 2010. He joined NTT Communication Science Laboratories in 1994. From 2003 to 2009, he was with Intelligent Robotics and Communication Laboratories, Advanced Telecommunications Research Institute International (ATR). His research interests include communication robots, sensor networks, pattern recognition, data mining in cyber-physical systems, and AI-based tailor-made education support. He is a member of the Institute of Electrical and Electronics Engineers (IEEE), the Society of Instrument and Control Engineers, and the Institute of Electronics, Information and Communication Engineers (IEICE).

Towards Reliable Infrastructures with Compressed Computation

Kengo Nakamura

Abstract

Contemporary society depends on several network infrastructures such as telecommunication and transportation. Analysis of such infrastructures is essential for, e.g., designing high-performance networks and finding vulnerable network components. This analysis often necessitates considering combinations of network components such as roads and optical fibers. However, combinations result in a prohibitive increase in computational time, preventing us from performing the analysis sufficiently in a reasonable time. In this article, I introduce efficient network-analysis algorithms using a decision diagram, which represents an enormous number of combinations in a compressed form, to tackle computationally challenging network-analysis problems.

Keywords: network infrastructures, compressed computation, decision diagrams

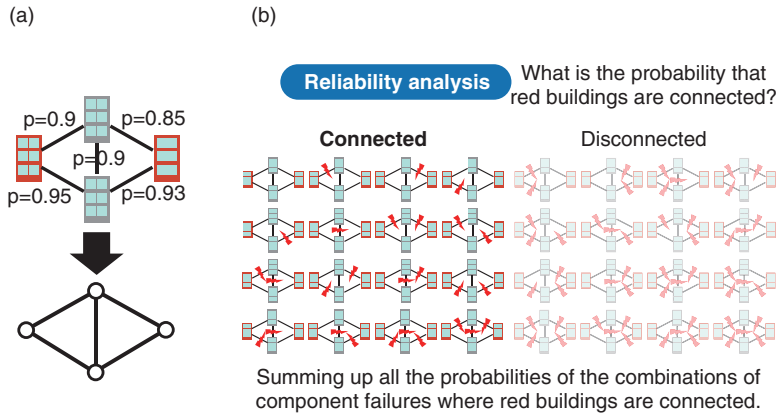
1. Network-analysis problems and combinations

Our society greatly depends on various infrastructures such as transportation, telecommunication, and electric-power distribution. What are the structural properties of such infrastructures? Highways spread like a mesh throughout Japan, and a core telecommunication network covers Japan through the laying cables. Therefore, modern infrastructures form network structures with many network components such as roads and cables.

There are various requirements for these infrastructures to work as bases for our society. For example, traffic jams should be avoided for road networks, and excessive delays and communication outages should be avoided for telecommunication networks. In accordance with these requirements, there are numerical indices for measuring the performance of infrastructures. For example, congestion is a performance index for road and telecommunication networks, and the robustness against component failure is a performance index for telecommunication networks. To develop high-performance, highly reliable infrastructures, it is important to develop algorithms for analyzing such performance indices. Examples of such analyses include congestion analyses to examine what components of the whole network become congested, reliability analyses to examine the robustness against failures and disasters, and vulnerability analysis to detect the weak or critical components of the network.

How can we analyze network infrastructures? Since it is difficult for computers to handle components, e.g., roads and cables, as just physical devices, we abstract network infrastructures by focusing on the connection between devices, such as those shown in **Fig. 1(a)**. Every component corresponds to a line (edge) connecting two nodes. Mathematically, this is equivalent to considering undirected graphs in graph theory. By developing network-analysis algorithms for handling the abstracted graphs, we can conduct analyses of the intrinsic structures of networks.

However, network-analysis problems are still difficult to solve with computers even after the abstraction. This is because a network infrastructure consists of multiple components, and there are exponentially many combinations of components. If a network consists of N components, the number of possible combinations is 2^N, which is the number obtained by multiplying 2 N times. Even if a network consists of only 50 components, the number of possible combinations becomes 1 quadrillion.



(a) A network is abstracted as a graph by focusing on the connection between nodes. (b) In reliability analysis, we need to examine all the combinations of component failures and sum up all the probabilities of connected combinations.

Fig. 1. Reliability analysis.

There are many network-analysis problems that must examine or count such an enormous number of combinations. In basic network reliability analysis, we want to compute the probability that specified nodes are connected via cables. In **Fig. 1(b)**, every node is drawn as a building. There are cases in which some components fail but the specified buildings are still connected via working cables. Thus, in computing the probability, we should consider two cases, work or fail, for every component, examine all the possible combinations of these cases, then add up all the probabilities of combinations where the specified building is connected. Similarly, in congestion analysis, we should examine all possible routes for computing what components are crowded. Since every route is a combination of components, and thus there are an enormous number of routes, the congestion analysis becomes a computationally difficult task.

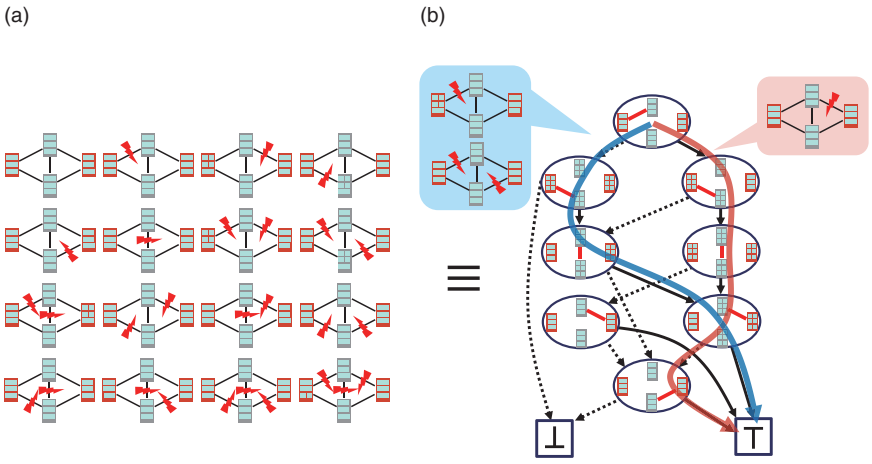
2. Decision diagrams and compressed computation

How do we cope with such an enormous number of combinations? We traditionally handled them by examining or counting only a small number of such combinations. This drastically reduces the number of combinations to examine or count, enabling us to resolve the issue of exponential computational time. However, this approach has a critical drawback in that the analyses become inaccurate because only a small number of combinations are examined. Since infrastructures are used by many people, thus have social importance, rigorous analyses are often needed at the cost of time.

This article considers the concept of compressed computation. Within this concept, we retain the combinations in a compressed representation and use it directly for analyses, i.e., computation, without decompressing it. If we can achieve this, we can conduct rigorous analyses because all the combinations are examined. The computational time may also significantly decrease because it may be proportional to the size of compressed representation.

One representation to achieve compressed computation is a decision diagram*. A decision diagram represents combinations by a diagram with vertices and arcs, each connecting two vertices. For example, **Fig. 2(b)** is a decision diagram representing the combinations drawn in **Fig. 2(a)**. All combinations can be obtained by tracing routes from top to bottom. Tracing a solid arc means that the component works, and tracing a dashed arc means that the component fails (see Fig. 2(b)). Solid and dashed arcs generally represent the presence and absence of a component, respectively. Decision diagrams achieve smaller representations by sharing common components of combinations. There are cases in which for a network with around 100 nodes, although there are 10^{41} combinations of component failures that two buildings are connected, a decision diagram can represent them with only 3000 vertices, which is a substantial compression. We can also conduct various computations,

* Decision diagrams: They correspond to data structures such as binary decision diagram and its variant zero-suppressed binary decision diagram. They are all data structures to represent combinations as a graph in graph theory.



Red and blue paths in the decision diagram represent the combinations drawn in red and blue bubbles, respectively.

Fig. 2. The combinations where red buildings are connected (a) and a decision diagram representing them (b).

such as optimization and counting, with decision diagrams without decompressing them. With the decision diagram drawn in Fig. 2(b), we can compute the number of combinations where the red buildings are connected even when additional conditions, e.g., a specific component must fail, are imposed. Such a computation can be conducted in time proportional to the number of vertices of the decision diagram. Therefore, decision diagrams can be seen as tools for compressed computation. Decision diagrams have been used for solving various network-analysis problems such as reliability analysis.

We at NTT Communication Science Laboratories have been developing algorithms for more advanced and sophisticated analyses by extending the types of computation and methods for compression within decision-diagram-based compressed computation. This article introduces two network-analysis algorithms developed from such research.

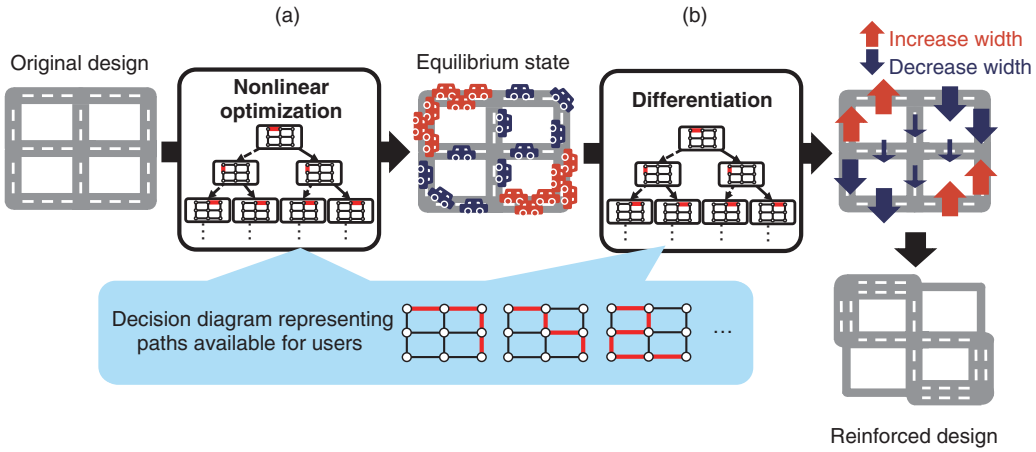
3. Infrastructure analysis by compressed computation

3.1 Infrastructure-design algorithm for reducing congestion

Within road and telecommunication networks, when many users' paths, e.g., the travel routes in road network or the routes of telecommunication network, overlap on a component, this component becomes congested and increases travel time. Thus, the operator of infrastructures wants to decrease the average travel time of users by widening the widths of roads and bandwidth of telecommunication cables to reduce the congestion. However, operators must assume that the users act selfishly when considering infrastructure reinforcement. An example of this is when a traffic jam occurs on highways, every user continues to use highways instead of bypasses if the travel time on highways is still shorter than that on bypasses.

What is the best way to reinforce an infrastructure under such a situation? In fact, there are cases in which, by widening some roads' widths or paving new roads, more users rush to use these roads, which incurs longer traveling time than before. Such a phenomenon is called Braess's paradox in traffic engineering. Braess's paradox is closely related to the state called the equilibrium state. When users use an infrastructure selfishly, they switch the path when there is a path with shorter traveling time than the currently used path. After every user repetitively switches the path like the above, all users' traveling time will eventually become the same, and every user will choose the path with the shortest traveling time at this point. This state is called an equilibrium state. To decrease the average traveling time, we should reduce the congestion within the equilibrium state. However, just widening some roads' widths or paving new roads results in the change of the equilibrium state, which is the cause of Braess's paradox.

We therefore need to compute the equilibrium state before determining an infrastructure reinforcement that decreases the users' traveling time. Although the traveling time is the same for all users within the



The equilibrium state is computed by nonlinear optimization with decision diagrams. We then compute the changes in the traveling time when the road width is slightly modified by differentiation with decision diagrams. Finally, these results are reflected on the design.

Fig. 3. Outline for infrastructure-design algorithm that reduces congestion.

equilibrium state, each user's path may vary. Therefore, the equilibrium state is formed from a combination of an enormous number of paths, i.e., a combination of combinations. This makes the problem of computing the equilibrium state much more difficult. It is also difficult to determine a reinforcement that reduces the traveling time of the equilibrium state.

We developed an infrastructure-design algorithm for determining a reinforcement that decreases the traveling time of the equilibrium state by compressing all the paths that users can choose into a decision diagram and conducting compressed computation with it (**Fig. 3**).

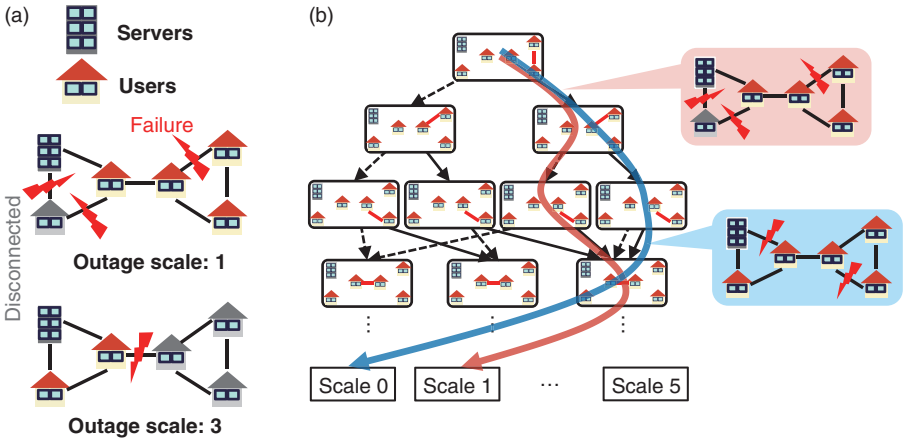
Although computing the equilibrium state is difficult because the result is a combination of combinations, we focus on the fact that it can be solved using a nonlinear optimization problem subject to combinatorial constraints. Solving this optimization problem traditionally requires examining all the paths one by one. However, we proposed an algorithm to solve this nonlinear optimization problem by compressed computation with decision diagrams, enabling us to compute the equilibrium state in a reasonable time [1] (Fig. 3(a)). Our algorithm then computes the differentiation with respect to the road width, i.e., the changes in the equilibrium state and traveling time when the road width is slightly modified, by compressed computation. This reveals the component to reinforce that reduces the average traveling time [2] (Fig. 3(b)).

The computational time with this algorithm is proportional to the size of the decision diagram, whereas that of the conventional algorithm is proportional to the number of paths. In the setting of multi-location telecommunication, we can achieve a speed-up of 10^{25} times by representing 10^{28} paths as a decision diagram of 10,000 vertices. In the future, we want to resolve various congestion problems such as traffic jams in road networks and delays in telecommunication networks through designing network infrastructures with this algorithm.

3.2 Computing the probability of outage per outage scale

The components of infrastructures, such as cables, occasionally but inevitably fail because they are physical equipment. Therefore, infrastructures are required to be robust against component failures in addition to being high performance during ordinary times. To assess the robustness against component failures, a reliability analysis such as that shown in Fig. 1(b), i.e., the computation of probability that specific nodes are connected, has traditionally been conducted. With a decision-diagram-based compressed computation, we have conducted exact, i.e., non-approximated, computation of the reliability for real networks with around 200 nodes.

However, when an outage occurs, the scale of outage is also an important index. Large-scale outages that affect many users should be less likely to occur than small-scale outages. However, traditional reliability analyses do not take into account the scale of outages. We want to analyze the probability of the



(a) Explanations for outage scale. (b) A new decision diagram that divides the combinations of component failures in accordance with the outage scale.

Fig. 4. Outline of computing the probability of outage per outage scale.

occurrence of outages separately for small-scale and large-scale outages. In other words, we want to compute the outage probability for every outage scale.

In this problem, we assume that network nodes are categorized into servers and users. We define the outage scale as the number of user nodes that are disconnected from any server, as shown in **Fig. 4(a)**. It should be noted that the outage scale is not proportional to the number of failed components. In the upper example, there are three failed components, but the outage scale, i.e., the number of disconnected users, is only one. In the lower example, only one component failure incurs three users' outage. We consider the exact computation of such outage probability per outage scale. This enables the operator of the infrastructure to check whether the designed network infrastructure meets a predetermined requirement for the occurrence probability of outage for every scale.

However, it is much more difficult to compute the scale-wise outage probability. This is because, in addition to the enormous number of combinations of component failures, we should consider the combinations of the users disconnected from servers. The conventional compressed reliability computation algorithm can calculate the probability that specific users are disconnected from servers if the specified users are fixed. We can compute the scale-wise outage probability by repetitively calculating it for all the combination of disconnected users. However, it is unrealistic because compressed computations are needed 1 quadrillion times for only 50 users.

While the conventional decision diagram divides the combinations of component failures in accordance with the occurrence of outages, we developed a decision diagram that divides them in accordance with the outage scale [3], as shown in **Fig. 4(b)**. With this new decision diagram, we developed an algorithm to compute the outage probabilities for all outage scales with only one compressed computation, yielding a substantial speed-up compared with the conventional compressed reliability computation algorithm. For a network with around 50 nodes, e.g., a network where each prefecture in Japan has a node, we can compute the scale-wise outage probability within one second, which is about 100,000 times speed-up compared with the current algorithm. For a network with around 100 nodes, although its difficulty increases 2^{50} times, i.e., around 1 quadrillion times, we can compute the scale-wise outage probability in around one hour, which is a reasonable time.

The proposed algorithm contributes to the highly reliable design of contemporary and future network infrastructures because it enables us to rigorously check whether the designed network meets the scale-wise requirements of outage probabilities. We will develop an algorithm for automatically designing networks where large-scale outages rarely occur by extending this approach.

4. Conclusion and future directions

We introduced two network-analysis algorithms with compressed computation using decision diagrams. We developed the infrastructure-design algorithm to

reduce congestion by using a novel compressed computation that enriches the ability of decision diagrams, while the algorithm for computing the scale-wise outage probability for every outage scale was developed by establishing a new compression method, i.e., a new decision diagram. We also developed various network-analysis algorithms by extending the decision-diagram-based compressed computation, e.g., the computation of the variance of network reliability [4] and that of the expectation of the number of users connected to servers [5]. We will continue to develop efficient and fast algorithms for problems handling an enormous number of combinations, not limited to network-analysis problems.

Our algorithms are at the stage of basic research; thus, analyses of currently designing or operating networks have not yet been conducted, although experiments using real network topologies that were released on the web were conducted. Therefore, the next step will be to analyze the currently designing and operating networks with the proposed algorithms and obtain insight for real network infrastructures.

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Human-centric Image Rendering for Natural and Comfortable Viewing—Image Optimization Based on Human Visual Information Processing Models

Taiki Fukiage

Abstract

As display technology and devices advance, using any surface or space as a display screen is becoming possible. However, emerging technologies that use projectors and see-through displays face challenges in maintaining consistent image quality, as the appearance of the displayed image can vary significantly depending on factors such as ambient light and background patterns. The key to solving this problem is understanding how the human visual system works. In this article, I introduce an approach that addresses this issue by modeling the visual information processing of the human brain. This model enables us to optimize displayed images to ensure they are perceived as intended despite environmental variations.

Keywords: media display technology, human information science, visual information processing model

1. Media technology based on understanding of human vision

Visual media, which are media for transmitting and sharing visual information, have evolved in various forms from paintings and photographs to televisions, projectors, smartphones, and head-mounted displays (HMDs)[*1]. These media have become indispensable in our daily lives. As technology advances, it is expected that information will be seamlessly presented in every space, effectively turning our surroundings into displays in the near future. How can we ensure that visual information is conveyed as intended across these diverse media? Ideally, reproducing a real scene would involve capturing and playing back all the information from the physical space. However, such ultimate media devices do not yet exist, and the degree of reproduction is constrained by the physical limitations of each device, such as the intensity, wavelength, and resolution of the light they can display. To convey information as intended within these physical constraints, it is crucial to understand how humans process, perceive, and recognize visual information.

Let us take an example of the technology behind color monitors. Human retinas have cells that respond to light in specific wavelength ranges, corresponding to red, green, and blue. Our perception of color arises from the combination of these responses—a phenomenon known as trichromatic vision. Leveraging this knowledge, modern displays recreate a vast spectrum of colors by blending red, green, and blue light. Similarly, three-dimensional (3D) televisions and HMDs convey 3D depth information on the basis of an understanding of human stereoscopic vision. Our brains perceive depth through binocular disparity—subtle differences in the images seen by each eye.

*1 HMD: A display device worn on the head. By projecting images directly in front of the eyes, it provides a highly immersive visual experience.

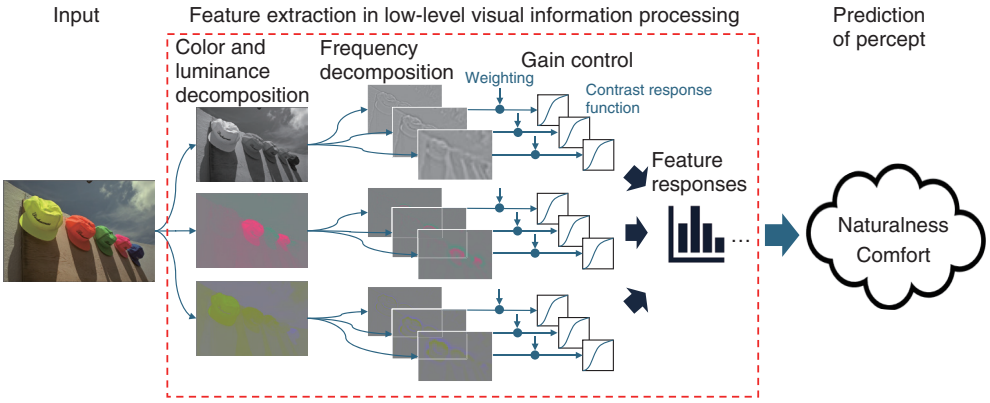


Fig. 1. An overview of visual information processing model.

Using this principle, 3D televisions and HMDs present different images to each eye, enabling viewers to experience a sense of three-dimensionality without the need for a physical 3D space. Thus, understanding and exploiting the characteristics of human vision allows for the efficient reproduction of perceived realities without fully replicating the physical world.

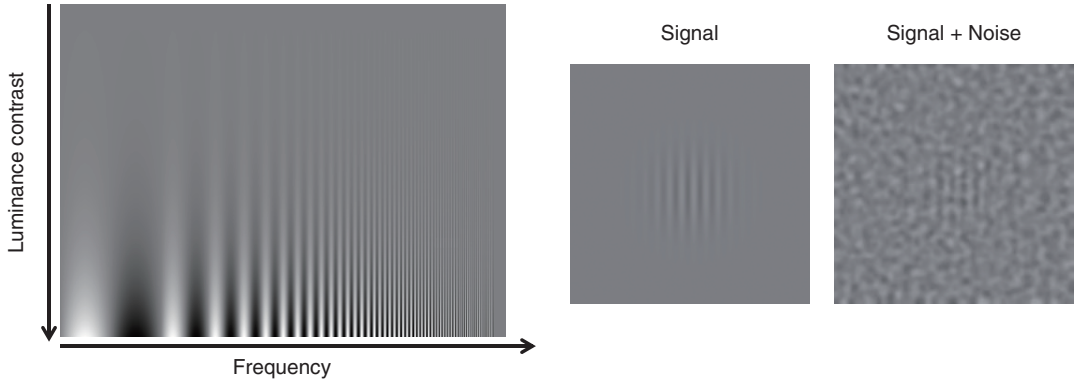
While the examples discussed thus far focus on designing display devices to align with human visual characteristics, the future of information presentation technology poses new challenges. In emerging technologies with which real and virtual information coexist, the appearance of displayed content is expected to change dynamically across different viewing environments. In such scenarios, predesigned devices alone will not be sufficient for optimal results. Instead, we will need to optimize the content itself in real time for each specific situation. To achieve this, an effective approach is to use a *visual information processing model* capable of quantitatively predicting perception for any given image and optimize the presented visuals on the basis of these predictions.

2. Visual information processing model

A visual information processing model is a mathematical representation of how the brain processes visual information. **Figure 1** illustrates the processing flow of a visual information processing model, which is discussed in this article. This model takes any image as input and extracts features we use when recognizing the input. It then predicts the intensity of our sensory response to these features (feature responses). Finally, the model estimates important indicators for visual presentation, such as naturalness of appearance and visual comfort, on the basis of these extracted features.

What exactly are these "features"? Our visual system extracts and uses various features from the information that enters the retina to recognize the world and guide actions. This feature extraction process is hierarchical. It begins with simple features such as color and luminance contrast (differences in luminance) in localized areas. It then progresses by integrating these features to detect more complex and global characteristics such as orientation, shape, texture, and eventually faces, objects, and landscapes. However, only a limited portion of this feature extraction process has been established as concrete, practical computational models. In the following sections, I focus on explaining low-level visual information processing, which has been used in the research examples covered in this article.

The specific process of feature extraction with a low-level visual information processing model is illustrated within the dashed box in Fig. 1. Let us begin by explaining *color and luminance decomposition*. Our retinas have cone cells, which are sensors corresponding to three wavelength bands: red, green, and blue. The light information received with these sensors is converted into a format called opponent colors, which emphasizes color differences while efficiently transmitting color information for subsequent processing. The color and luminance decomposition process mimics this color processing mechanism of the human visual system. It decomposes the input image by adding and subtracting the red, green, and blue color channels. This results in three components: one representing luminance and two opponent



(a) Contrast sensitivity for each frequency (b) Contrast masking effect

Fig. 2. Demonstration of contrast perception.

color components expressing the differences between red and green and between blue and yellow.

Next, the images corresponding to each color component undergo *frequency decomposition*. Frequency represents the spatial fineness of patterns. The human visual system has neurons that selectively respond to various levels of fineness, and these responses represent the frequency characteristics within the retinal image. The low-level visual information processing model uses image processing called *convolution* to reproduce this frequency-based information representation. Convolution yields images that represent contrast at various frequency scales. Finally, by applying weights to each frequency component, the model reflects the varying sensitivities of the human visual system to different frequencies [1]. **Figure 2(a)** illustrates this difference in sensitivity across frequencies. In this image, frequency increases (patterns become finer) from left to right, while physical contrast decreases from bottom to top. Although the physical contrast is constant at the same vertical level regardless of frequency, the boundary between visible and invisible stripe patterns appears as an upward curved line. This curve illustrates the visual system's varying sensitivity to different frequencies. Specifically, the visual system is most sensitive to patterns of intermediate fineness and less sensitive to very coarse or very fine patterns.

Finally, let us discuss *gain control*. This process is closely related to the perceptual strength of contrast. The visual system adjusts the gain of neural responses to accommodate a wide range of contrasts. Initially, the response increases rapidly with physical contrast, but it gradually levels off in high-contrast regions [2]. This behavior is illustrated by the contrast response function shown in Fig. 1, where the horizontal axis represents physical contrast and the vertical axis represents neural response.

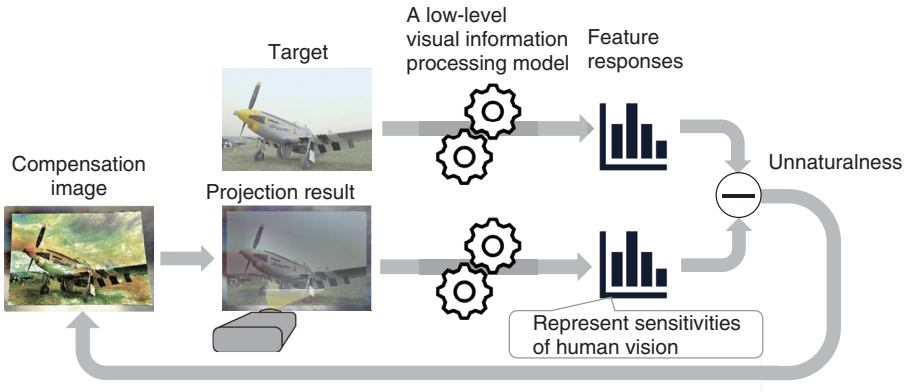
The contrast masking effect is a specific example that supports the presence of the gain control mechanism. In **Fig. 2(b)**, both left and right images have stripe patterns embedded at the same contrast. However, the stripes on the right, superimposed on background noise, appear much less visible. This can be explained by the strong neural response already triggered by the background noise, which makes the additional response to the stripes relatively small. In the low-level visual information processing model, these gain control mechanisms are mathematically expressed to quantitatively predict the perceptual magnitude of the visual system's response to each feature.

3. Optimizing display images using visual information processing models

As described above, a visual information processing model converts arbitrary images into features that reflect the sensitivities of the visual system. I will now explain what can be achieved using the model on the basis of research we have conducted.

3.1 Natural appearance manipulation of real object surfaces

First, let us look at research on spatial augmented reality (AR) using projectors. This technology, also known as projection mapping, allows manipulation of the appearance of real object surfaces. While it is



(a) Optimization of a compensation image with a visual information processing model

(b) Comparison of projection results

Fig. 3. Natural appearance manipulation of real object surfaces.

predominantly used for large-scale shows and demonstrations today, it has the potential for various information displays in more everyday settings. One technical challenge that needs to be addressed in such scenarios is the problem of interference between the object's own patterns and the projected image. A solution to this problem is a technique called radiometric compensation. This technique captures the projection surface with a camera and modifies the projected image to cancel out the surface patterns [3]. Since projectors cannot output negative light to cancel out light, for example, if the projection surface has a red pattern, cyan light is projected to neutralize the color, then the desired color is added to create the final projected image. However, in bright ambient light, the contrast of the surface pattern increases, requiring much stronger light to cancel it out. Typical projectors may not be able to output such strong light, making it impossible to fully compensate for the patterns.

Using the sensitivity characteristics of the vision system can be very effective in solving this problem. By prioritizing the reproduction of features to which humans are highly sensitive, while sacrificing features with lower sensitivity, it is possible to achieve perceptually natural results even if physical compensation is not perfect. We used a low-level visual information processing model to achieve this [4]. The specific procedure is shown in **Fig. 3(a)**. First, the target image and camera-captured image of the projection result are input into the model and converted into perceptual feature representations. Since these features represent the sensitivities of the visual system, the magnitude of the difference between these features can be regarded as the perceptual unnaturalness of the projection result. We then optimize the compensation image to minimize this unnaturalness. This automatically produces projection results that, while not physically identical to the target, are perceptually natural. Examples of actual optimization results are shown in **Fig. 3(b)**. While the physics-based method barely compensates for the surface

pattern, the perception-based compensation using a visual information processing model achieves a result that is perceptually much closer to the target image.

A similar method was also used to address the challenges of the projection technique called "HenGenTou" we previously developed. HenGenTou creates an illusion of motion in stationary real objects by projecting black and white dynamic patterns that express object motion [5]. However, there was a limit to the size of movement that could appear natural, and fine manual adjustments were previously necessary. To address this issue, we developed a method that uses a visual information processing model to predict the naturalness of the projection result and automatically optimize motion information [6]. This enables us to achieve maximum movement within a range that does not feel unnatural, enabling effective use of HenGenTou in interactive applications, such as moving the expressions of paintings to match user expressions.

3.2 Comfortable semi-transparent visualization on real-world scenes

In media technologies such as virtual reality (VR)*2 and AR*3, which are expected to cover the entire field of view, information is often displayed semi-transparently to avoid obstructing the view. However, in situations where the background real scene is constantly changing, it is generally difficult to maintain consistent visibility of the overlaid content. This is because visibility is greatly affected by the contrast of the background, as illustrated with the example of the contrast masking effect mentioned earlier. However, using a visual information processing model, it is possible to quantitatively predict changes in the visibility of such semi-transparent images. We previously proposed a technique that automatically adjusts transparency using a visibility prediction model that is based on a visual information processing model [7]. As shown in **Fig. 4(a)**, this method enables users to specify the target visibility rather than the physical transparency. When the content and background are given, the visibility prediction model predicts the visibility of the blended transparent image. The transparency map is then optimized to minimize the difference between the target visibility and predicted visibility. **Figure 4(b)** shows example results. The same content is displayed transparently over two different backgrounds. In the results of standard blending, even with the same transparency settings, the visibility of the content image varies greatly depending on the background. With the proposed method, however, the transparency is optimized in accordance with the target visibility map, resulting in consistent content visibility across different backgrounds. Therefore, our proposed method enables users to directly manipulate perceptual attributes such as visibility, resulting in more intuitive and precise control over transparent compositing. This method opens up exciting possibilities for applications in interactive media such as VR and AR, where it could enable semi-transparent displays that consistently maintain comfortable visibility across varying backgrounds.

4. Future challenges and prospects

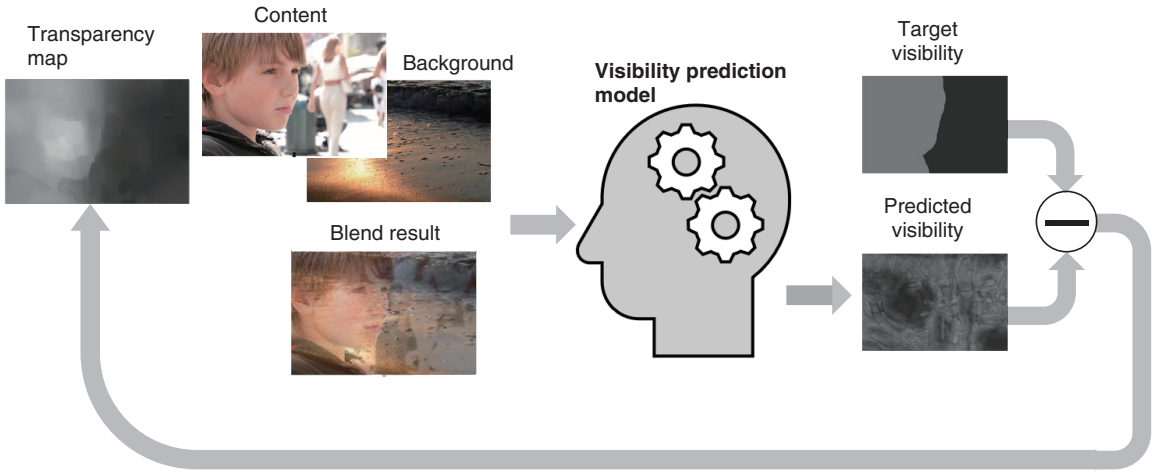
The optimization of content using visual information processing models is expected to become increasingly important in future media technologies. However, there are still many challenges to be addressed with this approach. First, the current visual information processing models for image optimization only cover a very small part of the complex visual information processing occurring in the human brain, corresponding to the initial stages. To advance future research, we need to progress towards modeling middle to higher-level information processing. For example, by enabling the prediction of texture, depth, motion, and material perception, it will be possible to adapt the presentation images more flexibly without changing these impressions.

However, the construction of higher-level processing models faces limitations when using the component-based approach classically used in low-level visual modeling, which involves understanding and assembling visual information processing in small sub-processes. Deep learning models are considered promising to address this issue. By training deep learning models on tasks such as object recognition, they learn to execute complex information processing tasks autonomously, from analyzing input images to generating task-specific outputs. It is noteworthy that the similarity between deep learning models trained for object recognition and human brain information processing has been revealed from various perspectives [8].

Nevertheless, these models do not quantitatively match human perception, thus cannot be directly used for image optimization. There are also reports

*2 VR: A technology that immerses users in a virtual visual world created using computers.

*3 AR: A technology that overlays virtual information on the real world, making information delivery more intuitive and convenient.



(a) Optimization of transparency map by visibility prediction using a visual information processing model

(b) Comparison of blend results

Fig. 4. Comfortable semi-transparent visualization using a visual information processing model.

suggesting that as performance improves, the divergence from human perception increases [9]. In the future, it will be necessary to develop methods to train deep learning models while enhancing their alignment with human perception.

Along with advancing the modeling of visual information processing, it is crucial to clarify the necessary conditions for naturalness and comfort from a human perspective. As seen in examples such as Escher's impossible staircase, humans can perceive physically impossible situations as natural at first glance. Therefore, the distribution of images that humans perceive as natural is thought to have a broader range than the distribution of images faithfully reproduced according to physics. By accurately estimating the spread of this distribution, we can expect to further expand the range of visual expression within various environmental and physical constraints.

Some of the results introduced in this article are from joint research with the University of Tokyo.

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Fast Knowledge Discovery from Big Data—Large-scale Data Analysis with Accuracy Guarantee via Efficient Pruning Methods

Yasuhiro Fujiwara

Abstract

There is growing interest in effectively using artificial-intelligence-based data analysis. Unfortunately, analyzing large-scale data incurs excessive computation costs. While approximate methods are commonly used to reduce computation costs, they cannot yield exact results; they sacrifice accuracy to improve efficiency. This article introduces representative methods of pruning unnecessary computations for fast and accurate data analysis.

Keywords: large-scale data, data analysis, efficient processing

1. Data analysis for large-scale data

Interest in data science has surged. One sign of this trend is the Harvard Business Review's 2012 introduction of data scientists as "the sexiest job of the 21st century." Many companies actively use data science, and numerous universities are now dedicated to cultivating talent to support this field. This trend has intensified annually, highlighting the growing importance of data science. One reason for the heightened interest is that companies can enhance business value by deriving effective marketing strategies from data analysis. The Economist's article, emphasizing data's value with the phrase "data is the new oil," also contributed to the widespread recognition of data analysis's importance.

The volume of digital data, which is the subject of data analysis, has been increasing rapidly. According to market research reports, the amount of digital data, which was approximately 12.5 zettabytes (around 1.25 billion terabytes) in 2014, is predicted to reach about 181 zettabytes (around 18.1 billion terabytes) by 2025. Extracting patterns and trends from such a vast data pool to support human decision-making is essential for effectively using this new resource called data. However, a significant challenge is that data analysis on such a massive scale incurs enormous computational costs due to the complexity of data analysis.

Approximate computation is seen as a reasonable way of reducing such computational costs. However, approximate computations emphasize speed over precision, resulting in a trade-off between computation time and analysis accuracy. Therefore, reducing computation time lowers analysis accuracy, and improving accuracy increases computation time. Since data analysis is used to support human decision-making, degrading the rigor of analysis results is not desirable.

My research colleagues and I are advancing research and development activities to build a machine learning platform that achieves both speed and rigor in data analysis (**Fig. 1**). A key to this platform is computational pruning. Computational pruning accelerates processes by eliminating unnecessary computations without compromising the accuracy of the results. This article introduces three representative pruning methods: (1) omission of computations

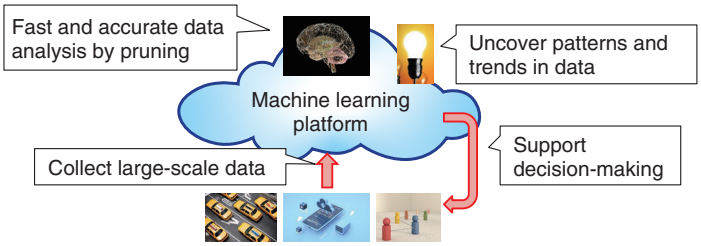
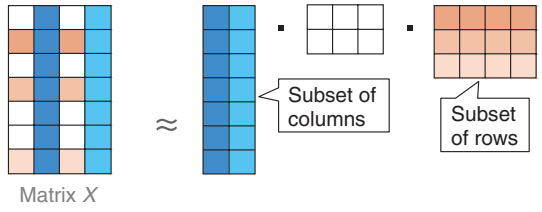
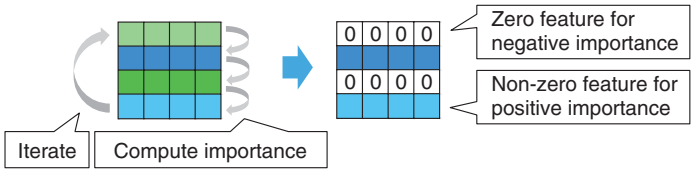


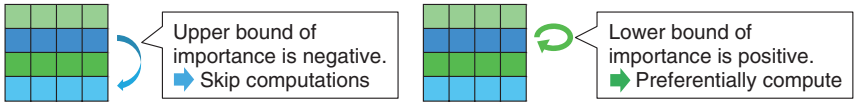
Fig. 1. Machine learning platform.



(a) CUR matrix decomposition



(b) Parameter matrix



(c) Computational pruning

Fig. 2. Efficient CUR matrix decomposition.

using upper and lower bounds, (2) termination of computations that cannot yield solutions, and (3) fast computations through optimistic processing.

2. Omission of computations using upper and lower bounds

First, I introduce a pruning method that uses upper and lower bounds to omit computations. This method rapidly identifies unnecessary processes by using upper and lower bounds of scores to skip unnecessary computations. An example of this pruning method is the acceleration of CUR matrix decomposition.

CUR matrix decomposition decomposes a given matrix X using its subsets of rows and columns (**Fig. 2(a)**). In Fig. 2(a), matrix X has the size of 7 × 4, and in CUR matrix decomposition, this matrix is represented using two blue subsets of columns and three orange subsets of rows. CUR matrix decomposition can extract important features from high-dimensional data by finding characteristic subsets of rows and columns that well represent the given matrix. For instance, time-series data generated over long periods from high-functioning sensors in a

factory can be represented as a matrix of sensor count × time length, resulting in a very large number of rows and columns. By applying CUR matrix decomposition, we can identify the significant rows and columns that represent the matrix well, allowing us to pinpoint characteristic sensors and time periods from massive data, which yields effective factor analysis for enhancing factory productivity.

In CUR matrix decomposition, a parameter matrix corresponding to each feature in matrix X is introduced to calculate the importance of each feature. Important features are extracted by setting features with negative importance to zero. In **Fig. 2(b)**, the parameter matrix has four rows corresponding to each column's features in matrix X in Fig. 2(a). In Fig. 2(b), the first and third rows of the parameter matrix are zero, indicating that the features of the first and third columns of matrix X in Fig. 2(a) are not important. In contrast, the features of the second and fourth columns are important. Although CUR matrix decomposition extracts important features from the parameter matrix, it requires iterative calculations, which are computationally expensive, making it difficult to apply it to large-scale data.

We proposed a method to rapidly execute CUR matrix decomposition by lightly calculating the upper and lower bounds of importance [1]. This method accelerates the iterative calculation of importance. As shown in **Fig. 2(c)**, if the upper bound of importance is negative, the exact importance will also be negative, enabling us to skip the calculation of that feature. If the lower bound of importance is positive, the exact importance will also be positive, so we prioritize calculating that feature. By using the upper and lower bounds of importance, we can omit unnecessary calculations and focus on computing the features with non-zero importance, thus accelerating CUR matrix decomposition.

3. Termination of computations that cannot yield solutions

Next, I introduce a method to accelerate processes by terminating computations that cannot yield solutions. This method maintains patterns that failed during the search process, terminating the process early when these patterns reappear. An example of this pruning method is the acceleration of subgraph search.

Subgraph search is a process of finding subgraphs with the same structure as the query graph within a large data graph in which the nodes are labeled. In

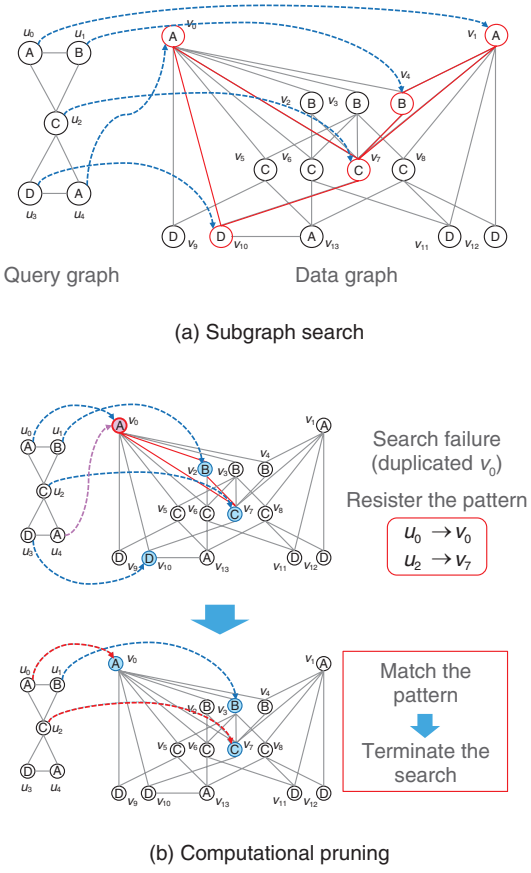
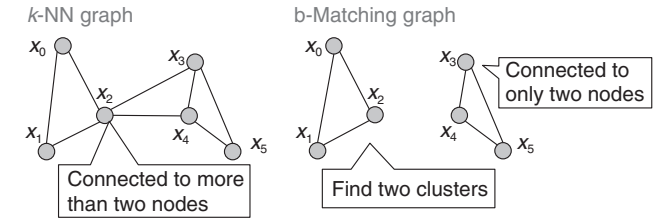


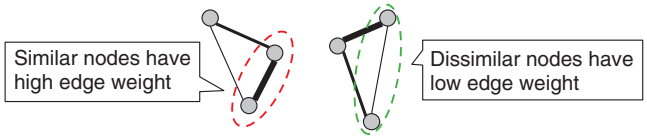
Fig. 3. Efficient subgraph search.

Fig. 3(a), the query graph consists of two triangles with labels A, B, C, and C, D, A; the corresponding red subgraph in the data graph also consists of triangles with the same labels. An application of subgraph search is the search for organic compounds. The bond relationships between molecules of organic compounds can be represented as graphs, and compounds with common bond relationships are known to have similar properties. Using subgraph search to find organic compounds with the same bond relationships, compounds with properties similar to the query can be discovered. However, subgraph search requires mapping each node of the query graph to the data graph, leading to exponential time complexity concerning the size of the graph. Therefore, subgraph search incurs excessive processing time as the data graph becomes large.

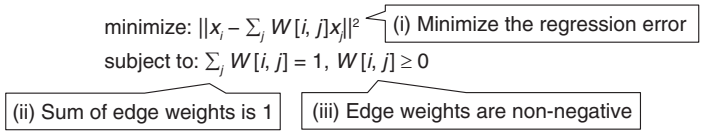
We proposed a method to maintain the patterns of failed mappings and terminate the process early if these patterns reappear during the search process [2]. In **Fig. 3(b)** (upper), mapping node u_0 with label A to



(a) Structure of b-Matching graph



(b) Edge weights in b-Matching graph



(c) Edge weight computation

Fig. 4. Efficient b-Matching graph.

v_0, u_1 with label B to v_2, u_2 with label C to v_7, and u_3 with label D to v_{10} causes node u_4 with label A to be forced to map to v_0, leading to a failure. Investigating this failure reveals that mapping u_0 to v_0 and u_2 to v_7 causes the issue. Specifically, if we map u_2 of label C to v_7, the connected node of label D of which is only v_{10}, we must map u_3 to v_{10}, and since only v_0 is the node of label A connecting to v_7 and v_{10}, we fail to find a subgraph if we already have mapped u_0 to v_0. Hence, the pattern of mapping u_0 to v_0 and u_2 to v_7 is stored as a termination condition. If this pattern reappears during the search, the process is terminated early. In Fig. 3(b) (lower), mapping u_0 to v_0, u_1 to v_3, and u_2 to v_7 matches the stored termination condition, so the process is terminated without further exploration. Thus, terminating computations that cannot yield solutions prunes unnecessary processes, enabling faster subgraph search.

4. Fast computations through optimistic processing

Finally, I introduce a method that prunes computations through optimistic processing. This method temporarily removes a constraint to find a solution quickly then verifies if the obtained solution meets the constraint, which enhances speed. An example of this pruning method is the fast computation of b-Matching graphs.

A b-Matching graph is a neighborhood graph in which each data point is connected to a specified number of neighbor data points. While k-nearest neighbor graphs are often used, where each data point is connected to k neighbor data points, they can result in data points having more than k connections. In **Fig. 4(a)** (left), each data point is connected to two neighbors in a k-nearest neighbor graph, but data points x_2, x_3, and x_4 end up with more than two connections. In the b-Matching graph (Fig. 4(a), right), however, each data point has exactly two connections, capturing the cluster structure more effectively where no data point has excessive connections. Additionally, edge weights in a b-Matching graph are determined by data similarity. Specifically, in **Fig. 4(b)**, edges between similar data points that are close together have larger weights, while edges between dissimilar data points that are far apart have smaller weights. This makes b-Matching graphs

effective for capturing cluster structures, as similar data points within the same cluster are more likely to be connected. This property can be applied to tasks such as parking lot status estimation and credit card fraud detection by effectively estimating data labels from neighboring data points.

To compute a b-Matching graph, it needs to (1) find the specified number of neighbor data points for each data point and (2) compute the edge weights. The details of the finding neighbors are omitted here. For the edge weight computation, solving the optimization problem shown in **Fig. 4(c)** is required. In Fig. 4(c), x_i represents the i-th data point, and $W[i, j]$ represents the edge weight between the i-th and j-th data points. This optimization problem aims to minimize regression error, as shown in Fig. 4(c), while satisfying the constraints that the sum of edge weights equals one and edge weights are non-negative. Solving such constrained regression typically requires using an optimization solver, which incurs high computation costs, thus lengthening the time required to compute edge weights in b-Matching graphs.

We proposed a method for quickly computing edge weights in b-Matching graphs through optimistic processing, enabling faster b-Matching graph computations [3]. The method first minimizes the regression error to compute the edge weight by ensuring that the sum of the edge weights is 1 through regression analysis instead of an optimization solver. It then checks if the edge weights satisfy the constraint that the edge weights be non-negative. Since this method uses the solver only when the edge weights do not meet the temporarily removed constraint, we can reduce the number of times the solver is needed. Thus, optimistic processing enables rapid computations while maintaining the rigor of results by initially removing a constraint, quickly finding a solution, then ensuring the constraints are met.

5. Conclusion and future prospects

With the remarkable progress in database and Internet technologies, we can now collect and analyze digital data on an unprecedented scale. Thus, data are becoming an increasingly valuable resource and used across various fields to discover new insights and support decision-making. Our society is shifting toward leveraging this new resource, and this trend is expected to accelerate.

In response to this societal trend, our research team is working to develop a machine learning platform that provides fast and accurate data analysis. Specifically, we are focused on developing algorithms that can process vast amounts of data efficiently and accurately, as well as constructing efficient data management systems. Through these efforts, we aim to create an environment where more people can effectively leverage data.

In the future, we hope that our machine learning platform will be widely adopted as a fundamental part of social infrastructure and that innovative applications leveraging data analysis will emerge across various fields. To achieve this vision, we will continue to pursue cutting-edge technologies and maximize the potential of data analysis.

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The Crux of Human Movement Variability

Atsushi Takagi

Abstract

Despite intense training, even a seasoned baseball pitcher has difficulty throwing a ball to the same location repeatedly. I describe my research team's finding that such movement variability comes from muscles that activate at imprecise times and introduce a new method that uses a smartphone to robustly quantify movement variability, which is tightly related to the arm muscles' timing precision. This useful method reveals how movement variability, a measure of dexterity, changes with growth and age, and it quantifies the degree of handedness and footedness.

Keywords: motor control, movement variability, timing

1. The importance of understanding how the brain moves the body as intended

Humans learn to move skillfully by activating the muscles on the basis of the sensory information the brain receives. Unlike robots, however, even the movements of skilled athletes are subject to variability, as movements cannot be repeated with perfect precision. This movement variability has long been the focus of attention in neuroscience.

To understand the mechanism of information processing in the brain that enables us to move our hands and feet freely, it is necessary to investigate how the variability of movement changes with growth and training and consider the mechanism behind these changes. NTT has been conducting research to understand the brain information processing involved in sensory and motor generation to develop information and communication technology that can be used by people. I introduce my research team's research into the nature of movement variability, which is deeply related to the ability of people to move as intended.

2. Previous research

People perform a variety of movements in their daily lives, such as throwing a ball or climbing stairs. In these movements, it is necessary to be able to move in the same way each time in accordance with the purpose of each movement. The mechanism of motor learning to achieve goal-directed movements has been studied extensively, and the information-processing mechanism of the brain has been clarified in previous research [1]. It is also known that movement variability decreases as motor learning progresses, but the mechanism that produces movements with less variability has not yet been elucidated.

Humans move by activating the muscles spanning a joint. Since it is known from previous research that the muscle commands to generate muscle activity are, in principle, subject to variation, and since the variability of muscle activity increases with its magnitude, the prevailing idea was that the origin of movement variability comes from such signal-dependent noise [2]. According to this theory, the greater the muscle activity, the greater the muscle-force fluctuation. Imagine a scenario in which the elbow is flexed to bring an apple to the mouth. The elbow accelerates by increasing the activity of the muscle working in the direction of movement (the flexor muscle) then decelerates by activating the antagonist muscle. The force exerted by the flexor and extensor muscles will peak at different times accordingly, so the elbow's force variability will vary the most when the flexor and extensor muscles are most active (**Fig. 1(a)**, force on an apple). According to signal-dependent

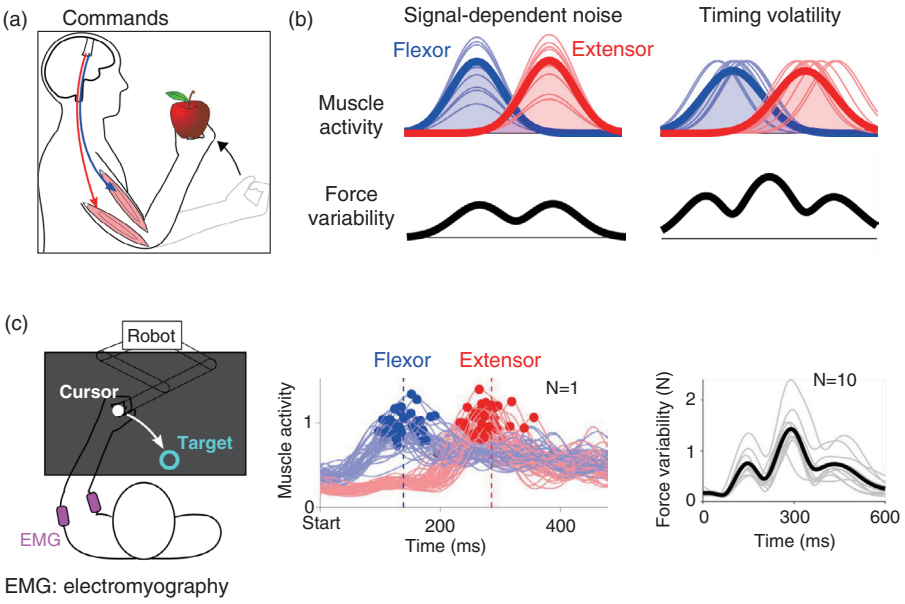

Fig. 1. Sources of movement variability.

noise theory, the force during the reaching motion would be expected to vary maximally or peak at two locations (**Fig. 1(b)**, left). To confirm this prediction, an experiment was conducted to measure the force and its variation when the elbow was flexed 50 times to reach the target [3]. Participants gripped the handle of a device that measured the elbow's force and position. Contrary to the prediction of signal-dependent noise theory, the force-variability time-series had three local maxima and not two (**Fig. 1(c)**, right). Therefore, this force variability cannot be explained by the previous theory. So where does the force variability come from?

3. Timing volatility as a source of movement variability

It has long been known that the timing of muscle activity is important in addition to its magnitude, but the effect of the timing of muscle activity on the variability of movement has not been fully investigated. In this study, we examined how the force to move a limb varies when the timing of activity of the flexor and extensor muscles is disrupted [3]. A previous study has shown that when electrical or magnetic stimulation is applied to the brain just prior to movement, the magnitude and shape of muscle activity during movement remains unchanged, and only the timing of the muscle activity is affected [4]. In other words, if brain information processing is perturbed, not only the magnitude but also the timing of muscle activity may be disrupted. Interestingly, the model predicted three local maxima in the force variability time-series during the reaching movement (Fig. 1(b), right). To test this prediction, we measured the activity of the flexor and extensor muscles during the movement and examined the relationship between the elbow's movement variability and the timing volatility of the elbow's flexor and extensor muscles. The timing of the activity of the flexor and extensor muscles differed significantly from trial to trial and was positively correlated with the elbow's movement variability. The magnitude of the muscle activity also varied from movement to movement, but there was no correlation between this and the elbow's movement variability. Thus, the experiment revealed that timing volatility is a significant factor in determining movement variability.

4. Muscles in the left and right arms have different timing volatility

Although it was clear that there was a correlation between the elbow muscles' timing volatility and the elbow's position variability, a new experiment was conducted to investigate whether a similar relationship could be observed in the left and right arms of the wrist, elbow, and shoulder joints [3]. In this

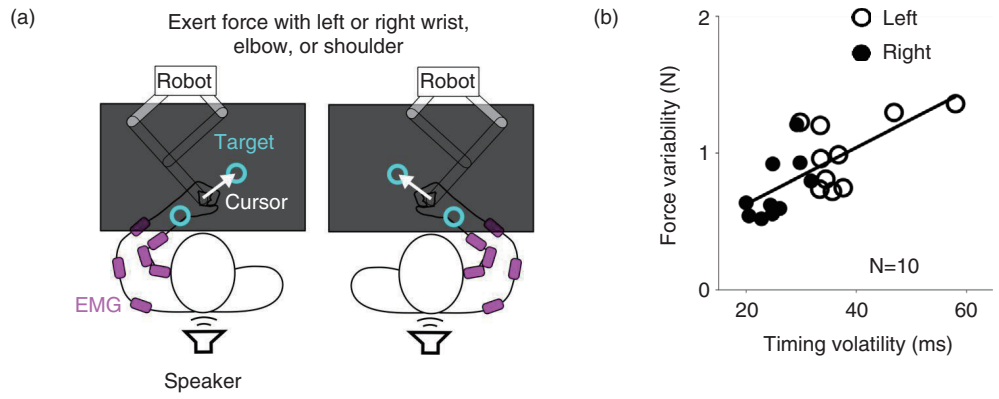

Fig. 2. Timing volatility is related to the arm's force variability.

experiment, the position of the handle of a device was controlled so that it would not move, and an arrow on the screen was programmed to indicate the direction of the force applied to the handle (**Fig. 2(a)**, left). The participants were asked to push or pull the handle in the indicated direction, relying on a sound that sounded at regular intervals. The direction of the force arrow was changed depending on which joint was being tested. The force and muscle activity obtained in these experiments revealed a positive correlation between the force variability and the timing volatility of the wrist, elbow, and shoulder muscles (**Fig. 2(b)**, right). With only right-handed participants, it was found that there was less timing volatility in the muscles of the right arm compared with the muscles of the left arm [3]. From these results, we considered the possibility that the higher accuracy of the dominant right hand may come from small timing volatility.

5. Relationship between dominant hand and movement variance

To further investigate the relationship between the dominant hand and timing volatility of the muscles, data from many participants is required. However, measuring muscle activity is time-consuming and labor-intensive, making it unsuitable for large-scale experiments. To facilitate the collection of data from many participants, we devised a simple method to estimate the timing volatility of the muscles controlling a limb [3]. This method examines the movement variability during repetitive circular movements at relatively high speeds. Since circular motion is made possible by activating multiple muscles in an orderly sequence, precise timing of muscle activity is required. Because of the relatively fast and simple repetitive motion, the acceleration variability can be evaluated with only a short recording. We therefore developed an algorithm to quantify the amount of variation in acceleration trajectories when a person undergoing measurement performs a 15-second repetitive circular motion while holding a smartphone or strapping it to the leg (**Fig. 3(a)**, upper) [3]. By expressing the difference between the three-dimensional acceleration trajectories of two consecutive cycles of cyclic motion on a distance scale for all movement cycles, the overall acceleration variability of the cyclic motion can be estimated. Participants were asked to complete the Edinburgh Handedness Inventory [5] and the Coren Footedness Inventory [6], which are conventional questionnaires used to determine the dominant hand and foot. The Edinburgh Handedness Inventory contains a total of ten items, and the respondents are asked to indicate the hand used in tasks such as writing or throwing a ball. The Edinburgh Quotient changes depending on the frequency of selecting the left hand (−1) and right hand (+1). If the Edinburgh Quotient was less than zero, the respondent was considered left-handed, and if it was greater than zero, the respondent was considered right-handed. The Coren Footedness Inventory included four items, and right-footedness was determined by asking the respondents to indicate the foot with which they kick a ball or the foot with which they take the first step when climbing up a flight of stairs.

Example acceleration trajectories from both hands and feet of a right-handed participant are shown in the lower part of Fig. 3(a). Upon visual inspection, the

Fig. 3. Forced use of the right hand affects the acceleration variability of the hands and feet.

variability in the acceleration trajectories of the dominant right limbs appears to be smaller relative to the non-dominant limbs. Using the developed algorithm, the acceleration variability can be quantified. To investigate the relationship between handedness and the acceleration variability, we evaluated the acceleration variability separately for right-handed, left-handed, and forced-handed individuals who answered that they were forced to switch from using their left hand to right hand at an early age (538 right-handers, 27 left-handers, and 43 forced-handers) (**Fig. 3(b)**) [3]. The right-handers showed greater variability in their left hand, while left-handers showed greater variability in their right hand. Thus, the acceleration variability of the dominant hand was smaller. Forced-handed individuals had less variability in both their left and right hands. In other words, forced use of the right hand results, on average, in a decrease in the acceleration variability of the right hand (i.e., increased dexterity), but no increase in the variability of the left hand (i.e., no decrease in dexterity). We then calculated the difference in the acceleration variability between the left and right hands of right-handed, left-handed, and forced-handed individuals (**Fig. 3(c)**). When left-handers were forced to use their right hand from an early age, the balance between the left and right hand's acceleration changed considerably towards stronger right-handedness.

6. Forced use of the right hand affects foot acceleration variability

Although we found that forced use of the right-hand reduced the acceleration variability of the right hand, we also examined the effect of forced correction on the feet. Foot variability was also analyzed separately for left-handed, right-handed, and forced-handed groups (**Fig. 3(d)**). Interestingly, right-handed individuals had, on average, less variability in their right foot (i.e., they were right-footed), whereas left-handed individuals had no difference in the acceleration variability of their left and right feet. Despite only the hand being corrected, the acceleration variability of the right foot was, on average, smaller than that of the left foot in forced-handed individuals (**Fig. 3(e)**). These results indicate how prolonged training of the other hand not only changes the difference in the acceleration variability between the left and right hands but also affects the acceleration variability of the feet.

7. Movement variability changes with growth and aging

We showed how prolonged training of the right-hand affects the acceleration variability of the hands and feet. We then investigated whether the acceleration variability of the limbs changes with age. **Figure 4** shows the acceleration variability of the dominant and non-dominant limbs, quantified from data obtained from experiments on 608 participants

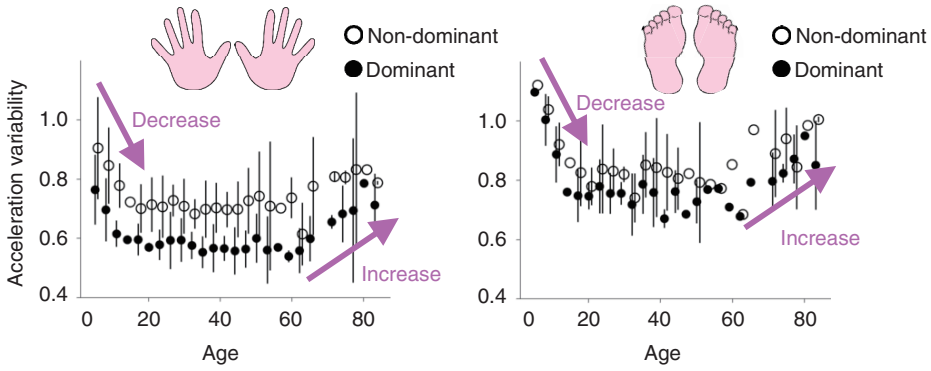

Fig. 4. Acceleration variability of the hands and feet decreases with growth and regresses with age.

ranging in age from 4 to 88. The graph shows that the acceleration variability for both dominant and non-dominant limbs decreased with growth, remained constant, and regressed with age. Although an increase or decrease in muscle strength is considered to have an effect, muscle strength is considered to increase until the 20s then begins to decline, so changes in muscle strength alone cannot explain the change in acceleration variability. Thus, changes in acceleration variability associated with growth and aging may well have to do with changes in muscle-timing volatility.

8. Conclusion and future work

I described how movement variability is affected by the timing volatility of muscle activity. By developing a method to evaluate the variability of limb movements using repetitive movements, the relationship between the dominant hand and muscle-timing volatility was clarified. Previous methods were developed to examine dexterity through work rate, for example, how many pegs can be placed in a hole in a certain time or how many small blocks can be carried from one box to another. However, these methods require special equipment and are difficult to implement out in the field. Therefore, it is difficult to measure the skill of many participants from a wide age range, and it has been challenging to examine the effects of growth, aging, or individual training on the ability to control limbs. Furthermore, the ability to control the feet has been assessed using measures such as the ability to balance on one foot for 10 seconds. However, this involves not just foot control but sensory processing of whole-body motion. Therefore, such a method is not sufficient for measuring the dexterity of foot movement.

We examined a method to visualize the acceleration variability by quantitatively evaluating the variability of repetitive movements over a short period. The results indicate that the acceleration variability of the dominant hand is related to smaller muscle-timing volatility. We also showed that the acceleration variability of not only the right hand but also the right foot was less than that of the left hand when the participant was forced to use their right hand from an early age. Furthermore, we found that the acceleration variability changed not only with training but also with age. The decrease in acceleration variability with growth suggests that motor learning to reduce the variability of movement progresses during growth. However, the increase in acceleration variability with age could be due to a breakdown in timing control, which may contribute to an increase in the risk of falling when walking.

Although growth and aging have been shown to affect the variability of arm and leg movements, the mechanism by which the timing of muscle activity, which determines variability, is disrupted remains to be clarified. If we can identify the brain region that produces timing volatility, we will be able to clarify why timing volatility changes with growth and aging. If the mechanism and training method for decreasing acceleration variability by training with the right hand as well as growth can be elucidated, it could be applied to sports training and rehabilitation. To validate such a training method, we need a technology that can easily evaluate the movement variability of a limb. The method introduced in this article can easily enable the visualization of the acceleration variability of movements by simply moving a smartphone. We believe this has potential in sports gyms, club activities,

rehabilitation facilities, and other settings, and can be used for individual training and rehabilitation.

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Addressing Supply Chain Security Risks through Security Transparency

Atsuhiro Goto and Yoshiaki Nakajima

Abstract

NTT has launched the Security Transparency Consortium to promote research and development of technologies for reducing supply chain security risks based on the key concept of *security transparency* and work with various companies forming the supply chain to mitigate such risks. In this article, we will introduce international trends related to supply chain security risks, relevant technologies, and an overview of the consortium.

Keywords: supply chain security, SBOM, security transparency

1. Emergence of unprecedented risks targeting supply chains

Cyber attacks have become a significant common threat to humanity, impacting the Internet, which supports economic activities and daily life and serves as a critical social infrastructure for health and life. Among the new risks related to cyber attacks, supply chain security risks are gaining global attention.

The services, systems, and products that people use are supported by diverse supply chains, from the design and development stage to the introduction and operation stage. If one of the suppliers in this supply chain is compromised, the impact propagates throughout the downstream of the supply chain. As services, systems, and products become more sophisticated and complex, the supply chain grows larger, and the scope of impact expands rapidly. It is also not uncommon for the downstream side of the supply chain where the impact propagates to be unaware of the existence of the supply chain, let alone understand it, making it difficult to avoid or reduce the impact. The risk arising from this is supply chain security risk, which has become significant and already caused harm.

In this context, NTT Social Informatics Laboratories considers that the main cause of supply chain security risks is the *invisibility* of the supply chain and its objects, such as services, systems, and products. Therefore, we are conducting research and development to fundamentally reduce these risks by using *transparency* as a key concept, enabling users to verify the components, such as software elements, included in these objects. Recognizing that cooperation among the various entities forming the supply chain is essential for reducing these risks, the Security Transparency Consortium was established in September 2023 as a platform for such collaborative efforts. The consortium's chairperson is Dr. Atsuhiro Goto, president of the Institute of Information Security, who is also an author of this article [1].

The next section explains supply chain security risks and introduce the initiatives led by the consortium to reduce these risks.

2. Risk classification and incident cases

As the integration of cyberspace and physical space advances, supply chains are diversifying and expanding. It is practically difficult to fully understand the entire supply chain and prepare for risks, making cyber attacks on the supply chain highly threatening. These risks can be classified as shown in **Fig. 1**.

Risk (1) refers to the risk that entities such as services, systems, products, etc., transferred in a supply chain will be compromised, and downstream business operators who trust upstream business operators use them without knowing the fact of compromise; as

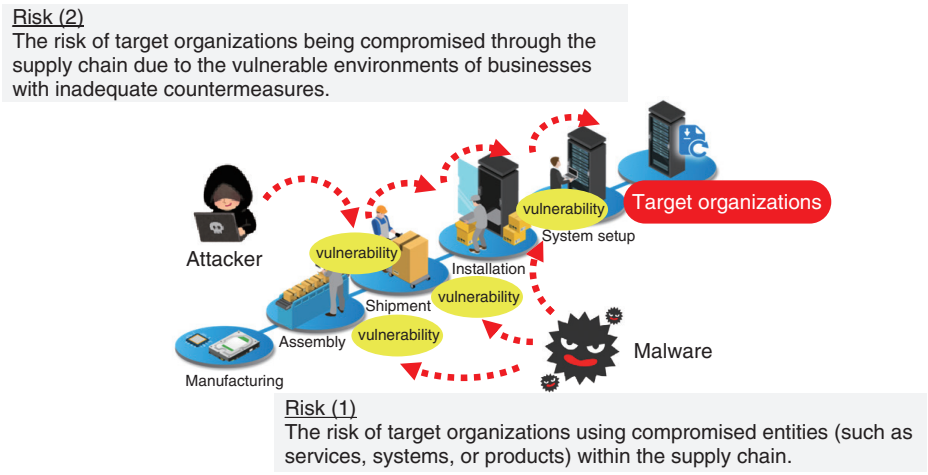


Fig. 1. Classification of supply chain security risks.

Table 1. Incident examples related to supply chain security risks.

Time of occurrence	Outline of incident	Category
December 2020	The update program for the system provided by SolarWinds was compromised, affecting approximately 18,000 customers through the supply chain.	Risk (1)
July 2021	The update program for the IT management system provided by Kaseya was compromised, impacting around 36,000 customers through the supply chain.	Risk (1)
October 2022	In a domestic medical institution, a catering contractor was compromised, and ransomware spread through the system integration between the two parties, infecting a large number of servers and devices (about 1,300 units) within the hospital.	Risk (2)
December 2022	A severe vulnerability discovered in the “Apache Log4j,” a de facto standard for log output libraries, exposed many systems to attack risks. The issue was exacerbated by the difficulty in identifying software using the affected version of Log4j within the supply chain.	Risk (1)

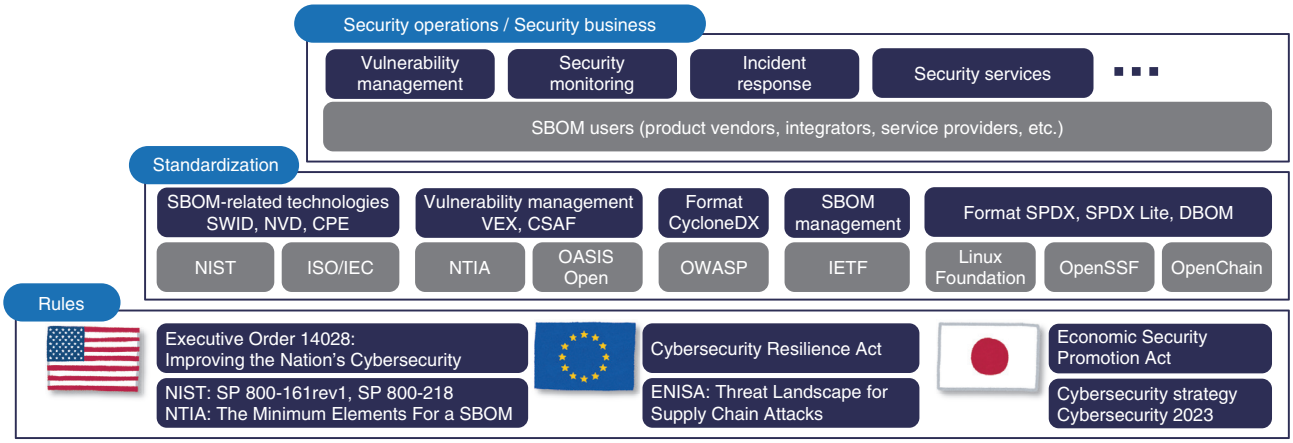
a result, they will be compromised. For example, there may be cases in which the software installed in the product is mixed with malicious software such as malware. It is also possible that vulnerabilities or unauthorized software might be introduced not only at the time of product introduction but also during software updates that are in operation.

In risk (2), the information technology (IT) environment of business operators that form a supply chain is compromised by cyber attacks, e.g., malware infection of company facilities, and hijacking of employee accounts, and various interactions with business partners, such as system linkage and email communication between business operators, are exposed to threats such as falsification, forgery, and malware infection.

There has been a series of incidents worldwide that have made us realize the emergence of such supply chain security risks. **Table 1** shows typical incident cases for each of the above categories.

3. National and industry trends in risk management

The occurrence of actual incidents has prompted governments, including the Japanese government, to recognize the importance and complexity of addressing supply chain security risks. Consequently, they are advancing various policies and regulations aimed at enhancing security. Related activities, such as standardization, are being promoted by industry groups, and it is expected that the security operations and security businesses of each business operator will be improved and developed on the basis of these activities. **Figure 2** shows an overview of the above.



CPE: Common Platform Enumeration
CSAF: Common Security Advisory Framework
DBOM: delivery software bill of materials
ENISA: European Union Agency for Cybersecurity
IETF: Internet Engineering Task Force
ISO/IEC: International Organization for Standardization/ International Electrotechnical Commission
NVD: National Vulnerability Database
OWASP: Open Web Application Security Project
SPDX: Software Package Data Exchange
SWID: Software ID
VEX: Vulnerability Exploitability eXchange

Fig. 2. Overview of trends related to supply chain security risks.

3.1 United States

In the United States, Executive Order 14028: Improving the Nation's Cybersecurity, issued in May 2021, has been a starting point for efforts to strengthen the security of the software supply chain, improve the reliability of software, and strengthen cyber-incident reporting requirements. National Institute of Standards and Technology (NIST), National Telecommunications and Information Administration (NTIA), Cyber Security Infrastructure Agency (CISA) and others in the United States have published best practices and guidelines for implementing measures based on this Executive Order [2].

A key element in this effort is a software bill of materials (SBOM). An SBOM is a list of components included in a software product and their information (software version information, dependencies between software, etc.). This information is expected to enable proper recognition of the existence of software that constitutes services, systems, and products throughout the supply chain, which leads to rapid and effective identification of vulnerabilities, risk identification, and implementation of necessary measures.

Efforts by the United States to popularize SBOMs are accelerating. In addition to standardizing SBOMs and publishing best practices for its operation, efforts are underway to require companies and critical infrastructure operators that do business with the U.S. government to prepare and provide SBOMs.

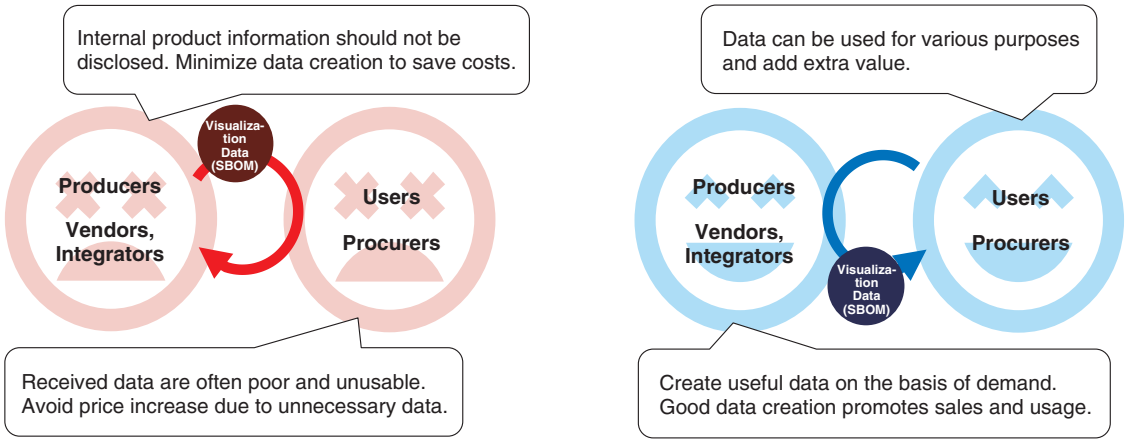
3.2 EU

The European Union (EU) is also promoting policies to address supply chain security risks. In particular, the Cyber Resilience Act (CRA) [3] published by the European Commission in September 2022 stipulates a variety of cyber-security-related regulations for products with digital elements, including supply chain security risks, and are scheduled to be enforced in 2024.

CRA is expected to clarify the responsibilities of the upstream (business operators) and the rights of the downstream (users) who form the supply chain and improve the environment for responding to risks throughout the supply chain. A business operator is obliged to provide information necessary to respond to cyber-security risks. As an SBOM is positioned as an important means to achieve this, it is expected that the creation of an SBOM will be widely sought in the EU as well as in the United States.

3.3 Japan

In the cyber-security strategy adopted by the Cabinet in 2021, the Japanese government has positioned the establishment of a foundation for ensuring supply chain reliability as key policy, and in its annual cyber security 2023 plan, the Japanese government states



(a) "Negative cycle" due to the gap between producers and users

(b) "Positive cycle" starting from the users' perspective

Fig. 3. "Negative cycle" and "positive cycle" related to visualization data.

that it will promote efforts to strengthen measures against supply chain security risks, including SBOMs.

As part of the above policies, the Ministry of Economy, Trade and Industry, the Ministry of Internal Affairs and Communications, and the Ministry of Health, Labour and Welfare are promoting various initiatives to popularize SBOMs, such as publishing guides on the introduction of SBOMs and vulnerability management using SBOMs. In the automotive industry, which is characterized by large-scale supply chains, there is a trend toward developing and adopting customized formats that take into account operational aspects, such as operational costs, of SBOMs.

4. What is required for risk management

Supply chain security risks, in which products, systems, and services are compromised through the supply chain, require countermeasures throughout the supply chain that extends throughout the world, including the suppliers of each component. SBOMs are being developed and studied by governments around the world and provide information (visualization data) to the supply chain that makes it easier to understand the content of objects to be protected and identify risks such as vulnerabilities hidden in them. SBOMs may increase the transparency of system configurations and reduce security risks. If visualization data can be shared throughout the supply chain from upstream to downstream and used for security measures, risks to the entire supply chain can be effectively reduced.

With the move toward making SBOMs mandatory, if efforts become more focused on the producer's perspective, such as the cost of generating visualization data, there is a risk that attention and efforts will be biased toward addressing problems on the producers. Therefore, as shown on the left of **Fig. 3(a)**, the goal may shift to producing visualization data within practical limits, potentially undermining the benefits that the visualization data were originally supposed to provide.

Therefore, we believe it is essential to also consider the user's perspective and approach the issue from both the user's and producer's viewpoints in a balanced manner, avoiding the above-mentioned bias. For example, identifying data conditions necessary for effective use of visualization data from the user's perspective enables producers to benefit from avoiding unnecessary generation of visualization data. If the creation of visualization data by the producers contributes to promoting product sales, it is expected that more resources to be allocated, further advancing the use of visualization data.

To truly address supply chain security risks, it is crucial for the diverse operators involved in the supply chain, both producers and users, to collaborate and tackle the issues from both perspectives.

5. The positive cycle of risk management the consortium aims for

Since the creation and provision of visualization

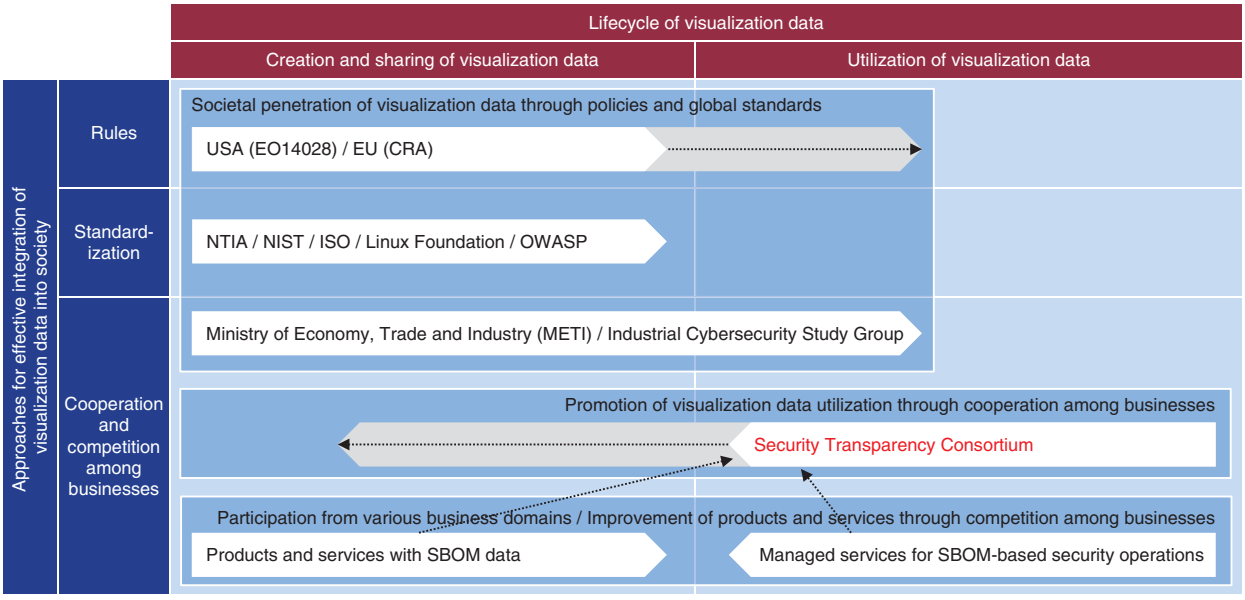


Fig. 4. Basic stance on consortium management.

data entails a cost burden on suppliers of products, it is essential to effectively use visualization data at a level commensurate with the cost. Effective utilization will encourage the creation and provision of visualization data, leading to a positive cycle that will further expand the use of visualization data (**Fig. 3(b)**).

We have established the Security Transparency Consortium to collaborate with various businesses that form the supply chain (product vendors, system integrators, security vendors, and businesses that use and operate services, systems, and products) and work on the *co-creation of knowledge* that contributes to the promotion of visualization data usage.

By promoting the creation and provision of visualization data and sharing the knowledge and expertise of each member, we aim to materialize and expand use cases. The three pillars of this consortium are as follows:

- We will work to materialize a wide range of use cases and methods for using visualization data. Specifically, we will analyze issues, examine solutions, and demonstrate the use of transparency enhanced by visualization data such as software configuration for security operations.
- With the participation of a variety of businesses, not limited to a specific industry or field, the study is conducted from a broad perspective that includes both the providers and users of the visualization data.
- With the aim of contributing to solving social issues, such as dealing with supply chain security risks, through the publication of the study results, we will also promote community activities that contribute to these efforts and cooperation with government agencies.

In advancing the above initiatives, ensuring ease of participation is particularly important to incorporate the insights of the diverse businesses that form the supply chain. Therefore, we operate the consortium with a clear definition of the collaborative domain and competitive domain. In our consortium, we define and publish the issues and challenges that members commonly face as the activity vision [4]. To address these issues, we discuss and co-create knowledge (such as insights on effectively using visualization data such as SBOMs) in the collaborative domain. During this process, each member refrains from bringing in their proprietary confidential information and operates solely using publicly available information. Members are expected to feed back the insights gained from the consortium activities into their own business (such as business or technology development) and strive for excellence in the competitive domain, thereby strengthening society's overall risk response capabilities. **Figure 4** summarizes the basic stance of consortium management as described above.

Through our consortium activities, we are dedicated

to promoting greater societal penetration of security transparency. By embracing this key concept, we aim to tackle various social challenges and work toward their resolution.

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Activities of the Security Transparency Consortium to Enhance the Effective Use of Visualization Data

Yusuke Kumazaki, Akira Yamada, and Ryota Sato

Abstract

To promote responses to supply chain security risks using visualization data, it is crucial for the various businesses that form the supply chain to collaborate and advance the effective use of visualization data in the collaborative domain. This article introduces the activities of the Security Transparency Consortium, established in September 2023 to promote *co-creation of knowledge* among these diverse businesses and promote the use of visualization data. It also discusses the challenges associated with promoting the use of visualization data.

Keywords: Security Transparency Consortium, visualization data, SBOM

1. The importance of collaboration in expanding the use of visualization data

As the importance of addressing supply chain security risks becomes increasingly recognized, both domestically and internationally, the adoption of visualization data, including a software bill of materials (SBOM), is progressing rapidly. For the widespread use of visualization data, it is essential that not only the producers but also the users within the supply chain collaborate to effectively use these data, making activities within the collaborative domain crucial. Section 2 introduces the activity vision and initiatives of the Security Transparency Consortium as part of the effort within this collaborative domain. Section 3 discusses the challenges faced by the producers in promoting the use of visualization data.

2. Activities of the Security Transparency Consortium

2.1 Activity policy and organizational structure of the consortium

The Security Transparency Consortium was established in September 2023 with the aim of promoting *co-creation of knowledge* among the diverse businesses that form the supply chain, promoting the effective use of visualization data. The consortium operates under the following guiding principles:

- To explore utilization methods across various fields, it targets a diverse range of businesses, including product vendors, system integrators, security vendors, and businesses that use or operate products, systems, and services.
- To ensure activities are based on mutual trust among businesses, new members are reviewed by a steering committee selected by the participating members.
- To facilitate participation, membership fees are not required or are kept minimal.
- The consortium does not handle intellectual

Table 1. Challenges faced by users.

(1) Lack of social penetration and awareness Due to a lack of understanding of the concrete value of visualization data, users are unsure of how to effectively use them, among other issues.	(5) Continuous utilization It is necessary to continuously obtain accurate visualization data when updating software, among other issues.
(2) Lack of standardized formats and data To handle visualization data uniformly, it is necessary for the users to establish clear guidelines for their application, among other issues.	(6) Supply chain coordination A system for mutual sharing between the producers and users across the multi-tiered supply chain is needed, among other issues.
(3) Insufficient technology and tools Automation is required to manage the vast amount of visualization data, among other issues.	(7) Impact of visualization data As visualization data increase security transparency, there will be a need to address issues that were previously unseen and unaddressed, among other issues.
(4) Cost inflation Efficient training of personnel and familiarity with related tools are necessary to adapt to the operational changes brought about by the introduction of visualization data, among other issues.	(8) Additional considerations Since the utilization of visualization data is not part of traditional operations, a review of operational structures may be necessary, among other issues.

property and focuses on the collaborative domain of participating businesses.
- Activities do not rely on confidential information from participants but use only the information that can be disclosed by each business.

The consortium operates through a structure consisting of a general assembly, steering committee for operational discussions, and working groups (WGs) dedicated to the co-creation of knowledge. The general assembly, where all member businesses participate, decides on basic policies. For matters, such as the admission of new members, decisions are made by the steering committee to ensure efficient decision-making. The actual co-creation of knowledge activities are carried out by WGs. There is one WG, the "Visualization Data Utilization WG," which meets 1–2 times a month, combining in-person and online formats, fostering active exchanges among members. The outcomes of these activities are openly shared on the consortium's website [1].

Since its inception, the consortium has expanded from 8 to 18 member businesses by July 2024, leading to a broader sharing of knowledge and a strengthened cooperative framework.

2.2 Activity vision for expanding the use of visualization data

To broaden the use of visualization data, it is crucial to accelerate efforts not only by the producers of the data but also by the users. In line with this, the consortium has published an activity vision of the consortium in February 2024 [2]. This vision focuses on addressing the issues and challenges faced by the users of visualization data, in addition to outlining the consortium's activity policy and content.

Visualization data encompass a wide range of information related to the configuration of software and hardware, risks (e.g., vulnerabilities), and states (e.g., actual usage reflected in device settings). The activity vision begins with discussions on the utilization of an SBOM, a representative method of expressing configuration information related to software included in products and systems. The vision then introduces the challenges that the users of visualization data face in ensuring supply chain transparency, with a particular focus on SBOMs.

3. Challenges faced by users of visualization data

There are still many issues to be solved in the use of visualization data. The consortium has summarized the challenges encountered by users in **Table 1**, and we provide a brief overview of each challenge.

As a societal challenge, there is the issue of the social penetration and recognition of visualization data (Challenge 1). Ensuring supply chain security requires not only the efforts of individual companies but also the collaboration of society to expand the use of visualization data across all companies that form the supply chain.

From a technical perspective, Challenges 2 and 3 must be addressed. These include the standardization of data formats and the development of tools and technologies to handle the vast amounts of visualization data. These are essential for promoting the effective use of visualization data.

Challenges 4 through 8 highlight the need for tools

and internal training for the producers to use visualization data effectively as well as agreements and collaborations between the users and producers. There is also a need to review and adapt organizational structures and practices both within and between organizations to fully harness the benefits of visualization data. Each of these challenges is explained in more detail as follows.

Challenge 1: Lack of social penetration and awareness

While the efforts of the producers in creating and providing visualization data are expected to lead to the widespread collection of such data across society, there is still a significant gap in the understanding and recognition of its value, particularly among users. As data collection and sharing progress, the increased availability of visualization information is anticipated to promote its use across various fields. However, awareness of how to use visualization data and its benefits is not sufficiently widespread. Many users still lack a concrete understanding of its specific value and how to use it effectively.

The uneven adoption of visualization data, concentrated within a limited number of companies, undermines its potential effectiveness in ensuring supply chain security. Therefore, it is crucial that the use of visualization data is uniform across all companies within the global supply chain.

It is important to note, however, that the challenge of social penetration cannot be resolved in isolation. The value of visualization data must be enhanced by overcoming the various challenges discussed later. As users begin to experience the tangible benefits of using these data, social penetration and broader adoption are expected to accelerate.

Challenge 2: Lack of standardized formats and data

An SBOM is a standard specification used to represent software composition and is highly valuable as visualization data. However, the existence of various standard specifications for SBOM data formats can lead to inconsistencies in representation. Since an SBOM allows for flexible description of data, the content often depends on the discretion of the creator. This can result in variations in the items included and the methods of description across different products, making it challenging to handle the data uniformly.

Discrepancies can arise in the outputs from various SBOM-generation tools, such as differences in capitalization, text format, and the omission of certain details. These variations in SBOM content can also stem from differences in how users intend to use the data. If industries or client companies start defining and requesting specific information according to their unique needs, multiple SBOMs with differing content could be created for a single product.

These inconsistencies in SBOM content significantly impact the quality of visualization data. In vulnerability management, if the quality of the visualization data used to identify vulnerabilities is not accurately assessed, unnecessary actions may be taken, or critical vulnerabilities may go undetected, leading to significant issues.

Challenge 3: Insufficient technology and tools

To effectively use visualization data, it is essential to collect comprehensive and accurate information from a wide range of businesses. Although various technologies and tools for handling visualization data are already available, the information they provide may not fully meet the needs of users in their specific use cases. This highlights the need for further development of technologies and tools as well as the creation of knowledge to use them effectively.

For widespread adoption of visualization data, it is crucial that affordable and user-friendly technological options are available. This would enable a greater number of businesses to easily integrate and use visualization data in their operations.

Challenge 4: Cost inflation

The cost of generating the necessary visualization data on the producer side is often reflected in the overall cost of providing products or services. Therefore, it is crucial that the tools and systems required for this process be affordable. On the user side, in addition to the cost of tool implementation, there is a need for efficient training of staff to adapt to the changes in operations brought about by the introduction of visualization data. During the initial implementation phase, it is essential to train personnel who can accurately understand and communicate the value of visualization data within the organization, making education costs a significant consideration.

As discussed in the "Challenge 2: Lack of standardized formats and data" section, the possibility of creating multiple different SBOMs for a single product can lead to increased costs for the producers. These additional costs can also impact the users, highlighting the need for cross-industry and cross-company efforts to standardize the required information. This standardization can help reduce the overall

burden of implementation costs on both sides.

Challenge 5: Continuous utilization

After a product is deployed, software updates are frequently executed, which can result in discrepancies if the visualization data obtained at the time of procurement no longer align with the current state of the product, system, or service. Such inconsistencies can lead to security management issues. Therefore, users need to ensure the continuous accuracy and relevance of the visualization data.

For those who are already managing vulnerabilities, it may be necessary to establish a smooth transition from their current vulnerability management practices to one that fully integrates the use of visualization data.

When users customize the products, the visualization data might also need updates to reflect these changes. In such cases, it is crucial to establish clear guidelines on the responsibility for maintaining the accuracy of the visualization data, ensuring that the entire product remains consistent and secure.

Challenge 6: Supply chain coordination

Information about the components of a product, including the SBOM, is often confidential to the product vendor. Therefore, such information should be disclosed only to specific parties, with appropriate security measures in place. If data are inadvertently leaked, they can be exploited for cyber attacks, so strict control is required.

Users are required to clarify the range of visualization data they expect to use. On top of that, consensus building in the supply chain is necessary to obtain the necessary visualization data. The supply chain for products, systems, and services is generally multistage, requiring cross-organizational cooperation between the producers and users of visual data through the supply chain. When software is procured based on a contract, it is possible to include the items for consensus building regarding visualization data in the contract.

In the supply chain, as well as inquiries and responses regarding product defects, it is also necessary to have a method for confirming the accuracy of visualization data and request corrections.

Challenge 7: Impact of visualization data

As visualization data become more widespread and enhance security transparency, it may require organizations to address issues that were previously unnoticed or unaddressed. While cross-referencing visualization data with vulnerability databases allows for efficient and comprehensive automated checks for known vulnerabilities, it also raises the possibility of detecting a large number of vulnerabilities. This could overwhelm the existing vulnerability management capabilities, necessitating the development of strategies to handle this influx effectively. Given the numerous vulnerability databases available, it is crucial to understand the characteristics of each and carefully select the most relevant ones for cross-referencing before proceeding.

The integration of visualization data may lead to a reassessment of existing security practices. In managing product vulnerabilities using SBOMs and external vulnerability databases, for instance, the matching process may reveal vulnerabilities that pose no actual threat based on how the components are used within the product. In such cases, combining SBOM data with VEX (Vulnerability Exploitability eXchange) can help streamline vulnerability management by providing context about the impact of each vulnerability on the specific product, improving operational efficiency.

Challenge 8: Additional considerations

The utilization of visualization data requires a reevaluation of existing workflows, as it introduces tasks not traditionally included in standard operations, relies on automation through various tools, and necessitates ongoing data updates. While security measures are typically managed by the information technology department, it is crucial not to overly burden them. Instead, a company-wide reassessment of operations is necessary to effectively integrate visualization data into security practices.

For the producers, it is also important to ensure that visualization data align with industry-specific regulations and supply chain models. While it is theoretically possible to generate comprehensive visualization data for every aspect of a product, in practice, the complexity of multi-tiered supply chains may require decisions about how deep into the supply chain data should be generated for each product. For products where the entire configuration or parts of it are not publicly disclosed, special consideration must be given to how these data are handled.

4. Conclusion

We have introduced the collaborative efforts and challenges within the domain of addressing supply chain security risks. Participants of the consortium

are actively sharing their operational insights and engaging in vigorous discussions within WGs to tackle these challenges and publish relevant knowledge and use cases. Through these discussions, new issues, such as the limitations of the current SBOM formats, have begun to surface—issues that were previously unnoticed. These insights will be continuously shared on the consortium's website.

To enhance supply chain security risk management across the industry, the consortium will continue to widely disseminate knowledge from a variety of perspectives, contributed by diverse businesses. Through these ongoing activities, we aim to foster a more secure and resilient supply chain.

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Enhancing Software Vulnerability Management with Visualization Data

Akimi Inoue

Abstract

To use visualization data effectively in software vulnerability management, it is essential to clarify its use cases. This article introduces examples of how visualization data can be used within organizational vulnerability management.

Keywords: Security Transparency Consortium, visualization data, SBOM

1. Key practices in managing software vulnerabilities with visualization data

In organizational software vulnerability management, four actions typically occur: investigating the presence of security issues, considering the impact of vulnerabilities and direction of countermeasures, formulating a countermeasure work plan, and implementing the countermeasures [1].

Investigating the presence of security issues refers to the process of examining acquired vulnerability information to determine whether vulnerabilities exist within the information systems and under what conditions problems may arise. Security operators review publicly available vulnerability information, identify the departments or information systems using software products with relevant vulnerabilities, and pinpoint the areas requiring attention. For instance, a security operator may notify relevant teams if any systems need urgent attention on the basis of information collected through external services providing vulnerability information. Upon receiving such notifications, system administrators report back to the security operator about whether the vulnerabilities pose any risk. The security operator then identifies the areas within the organization affected by the vulnerabilities and proceeds to the next action.

If vulnerability information is not appropriately shared both internally and externally, software users cannot implement the necessary countermeasures. The use of visualization data to share this vulnerability information is discussed later.

Considering the impact of vulnerabilities and direction of countermeasures involves clarifying the potential impact of the identified issues and evaluating methods for fixing or mitigating them. The number of reported software vulnerabilities has been increasing yearly, with 28,297 vulnerabilities reported to the National Vulnerability Database (NVD) in 2023 [2]. This amounts to more than 70 vulnerabilities being reported daily. While all vulnerabilities in the software used during system development should ideally be addressed, it is not realistic to deal with every reported vulnerability due to the associated workload and costs. Therefore, when addressing vulnerabilities, it is crucial to prioritize countermeasures on the basis of the severity of the impact on the system or organization. Establishing predefined priority indicators within the organization's security policy, considering the software used and the development style, is an effective approach.

In formulating a countermeasure work plan, a plan is created outlining the procedures and timeline for implementing the countermeasures. Factors such as costs and personnel are taken into account and plans for service downtimes and testing are considered.

Based on this plan, the implementing the countermeasures action is executed to complete the vulnerability response. Security operators can confirm the completion of a vulnerability response by verifying that the organization has carried out the implementing

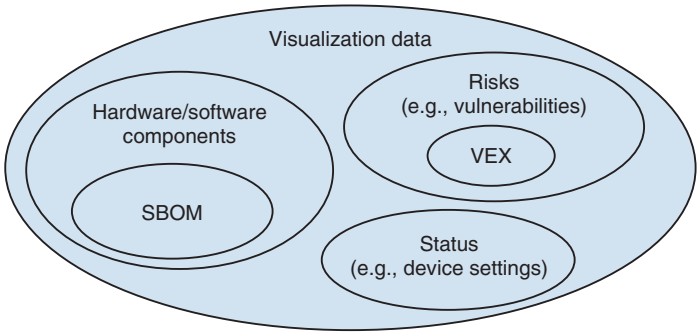

Fig. 1. Composition of visualization data [3].

the countermeasures action.

2. Software vulnerability management using visualization data

In this section, visualization-data use cases in software vulnerability management are introduced, including the structure of the visualization data.

2.1 Structure of visualization data and its application in vulnerability management

Visualization data refer to data that visualize the structure of software products or systems. As shown in **Fig. 1**, visualization data encompass a wide range of information, including configuration information (software and hardware components), risk information (such as vulnerability data), and status information (such as actual usage patterns) [3].

This section focuses on the use of two specific formats: a software bill of materials (SBOM), which represents configuration information, and Vulnerability Exploitability eXchange (VEX), which handles vulnerability information, to demonstrate how visualization data can be applied in vulnerability management.

An SBOM is a list of components and their associated information included in a software product. The National Telecommunications and Information Administration (NTIA) defines the minimum elements of an SBOM as supplier name, component name, version of the component, dependency relationship, author of SBOM data, timestamp, and other unique identifiers within the categories of Data Fields, which should be considered by organizations implementing SBOMs, as well as automation support and practices and processes [4, 5].

VEX is a machine-readable security advisory used to provide information to user organizations from software vendors and other stakeholders about whether a software product is affected by known vulnerabilities. The U.S. Cybersecurity and Infrastructure Security Agency (CISA) outlines the minimum requirements for information that should be included in a VEX document [6], and in Japan, discussions are underway on using VEX for vulnerability management.

As mentioned earlier, four key actions in vulnerability management were introduced. Among these, the use of visualization data in particular is expected to contribute to the actions of investigating the presence of security issues and considering the impact of vulnerabilities and direction of countermeasures.

The "Guide of Introduction of Software Bill of Materials (SBOM) for Software Management Ver.2.0 (Draft)" published by the Ministry of Economy, Trade, and Industry (METI) introduces processes such as vulnerability identification, vulnerability response prioritization, information sharing, and vulnerability response [5]. In this context, vulnerability identification refers to the process of identifying vulnerabilities within the software, vulnerability response prioritization involves evaluating vulnerabilities and determining the priority of responses, information sharing refers to sharing vulnerability information both inside and outside the organization, and vulnerability response involves taking some form of action to mitigate the identified vulnerabilities.

2.2 Investigation and analysis of vulnerability impact based on visualization data

When using visualization data in vulnerability management, there are two main perspectives: conducting investigation and analysis of vulnerability impact based on visualization data and using visualization

Table 1. Examples of vulnerability management actions and processes with visualization data.

Key practices	Processes with visualization data		
Actions	Processes	Use cases	Examples of visualization data
1. Security issue investigation	(1) Vulnerability identification	Conducting investigation and analysis of vulnerability impact based on visualization data	Software components (SBOM)
2. Impact and response assessment	(2) Vulnerability response prioritization	Using visualization data to understand vulnerability information	Vulnerability (VEX) system configuration
	(3) Information sharing	-	-
3. Response planning	(4) Vulnerability response	-	-
4. Response implementation		Updating visualization data for step (1) when component changes	-

data to understand vulnerability information. The former involves the users of the visualization data using elements such as software component information to carry out the vulnerability identification process. The latter refers to users leveraging the vulnerability information embedded within the visualization data to gather the necessary information for the vulnerability response prioritization process. When applying visualization data, it is effective to first determine which use case is more suitable for the organization then explore the appropriate method of utilization. The relationship between these perspectives is illustrated in **Table 1**.

In the following sections, how the elements of visualization data can be applied in each case is introduced.

First, let us discuss the use case of conducting investigation and analysis of vulnerability impact based on visualization data. In the vulnerability identification process, the goal is to collect information on the names of software affected by vulnerabilities and the specific versions that are vulnerable then investigate whether these software versions are used within the organization. When using visualization data to identify vulnerabilities, one can cross-reference the collected vulnerability information with software component information, such as an SBOM, which is one of the elements of visualization data.

In practice, when security operators within an organization perform this task, it is effective to establish a system that automatically cross-references the vulnerability information with the information listed in the SBOM by consulting services that provide vulnerability information, vulnerability databases, and various software vendor websites.

Figure 2 illustrates an example of the sequence of software vulnerability management steps when conducting investigation and analysis of vulnerability impact based on visualization data involving both security operators and system administrators.

Steps (1) to (4) correspond to the vulnerability identification process, step (5) corresponds to information sharing, and step (6) corresponds to the vulnerability response process. If a large number of vulnerabilities are detected in step (3), it may be necessary to establish priority indicators for responses in step (4) to execute vulnerability response prioritization and limit the scope of step (5) accordingly. Another important consideration when using visualization data is to recognize that after step (6) is executed, the software component information collected in step (1) may need to be updated. An example of a vulnerability response could involve changing the version of a software component. In such a case, if the version information in the component data collected in step (1) differs from the version information after step (6), future vulnerability responses might not be handled appropriately. Therefore, it is crucial to continue updating the component information as software configurations change, even after the initial collection and aggregation of data.

The expected benefits of this approach include reducing the labor required for vulnerability identification by the security operator/system administrator and mitigating the residual risk of vulnerabilities. In a proof-of-concept conducted by METI, it was reported that using SBOMs for vulnerability management reduced management labor by approximately 70% compared with traditional manual management methods [7].

2.3 Understanding vulnerability information using visualization data

Next, let us examine using visualization data to

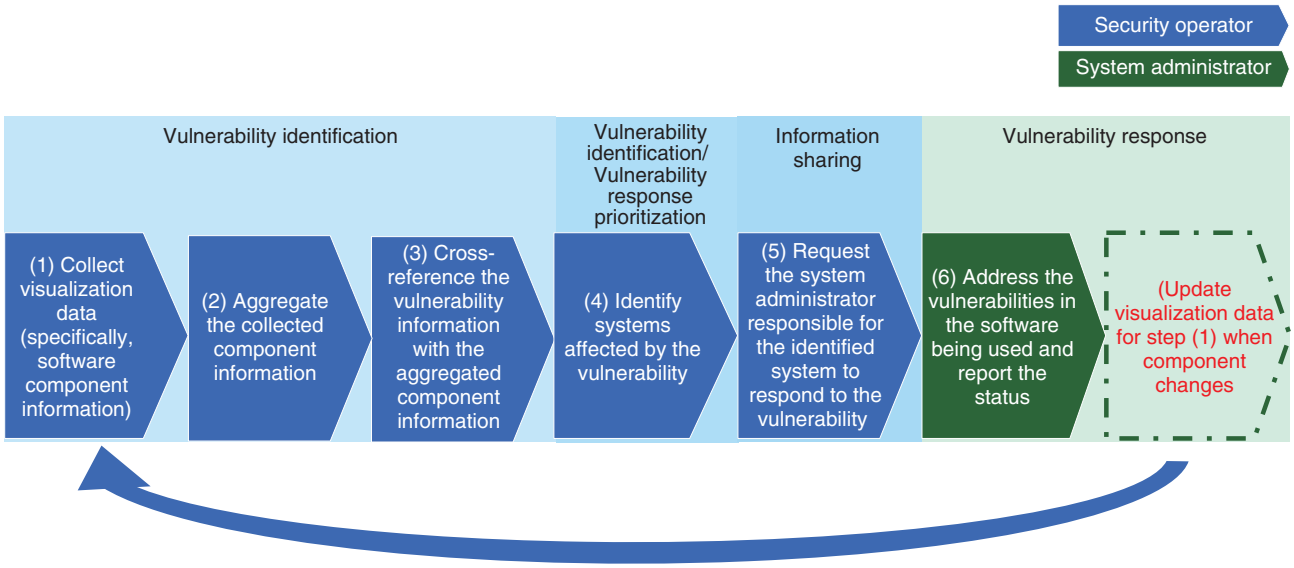

Fig. 2. Software vulnerability management when conducting investigation and analysis of vulnerability impact based on visualization data.

understand vulnerability information, as illustrated in **Fig. 3**. When applying visualization data to this scenario, it is expected to contribute significantly to the vulnerability response prioritization process.

In this process, vulnerability information is used in conjunction with system security settings and the security controls of access control devices. Software vulnerabilities often become a threat only when specific conditions are met. Information that confirms these conditions (such as settings or designs) needs to be verified by system administrators or users, while security operators must accurately convey the vulnerability information. There are also cases in which a software product may not be affected even if a vulnerability is found. In such cases, the software vendor must disclose this information, and users need to understand and respond appropriately. In Log4Shell (CVE-2021-44228), for example, even after the Log4j vulnerability was disclosed, it was necessary to determine whether the software products in use were affected. In such situations, there is a need for a system that uses visualization data to distribute impact information specific to each software product.

Specifically, product vendors would investigate the configuration of software components included in their software products and assess the impact of any vulnerabilities within those components on the overall software product. The results of this investigation would then be published as visualization data. This enables users to determine the impact without needing to directly consult the product vendor. Without the use of visualization data, however, software users would need to confirm with the product vendor whether a vulnerable software component is included in the product and, if so, whether it poses any impact.

With the increasing adoption of open source software (OSS), the number of OSS components used in a single software product is also on the rise. When managing vulnerabilities using visualization data, there is a concern that the more software components are used, the greater the number of detected vulnerabilities. In this context, when conducting investigation and analysis of vulnerability impact based on visualization data, verifying whether each software component's vulnerability in the software product actually requires action could be extremely time-consuming. Therefore, it is considered effective to use visualization data to share information on whether action is needed for software component vulnerabilities for each product, enabling more efficient vulnerability management.

2.4 Exchanging visualization data elements between companies

Managing software vulnerabilities using visualization data involves combining various types of information. Visualization data represent a subset of the information necessary for software vulnerability

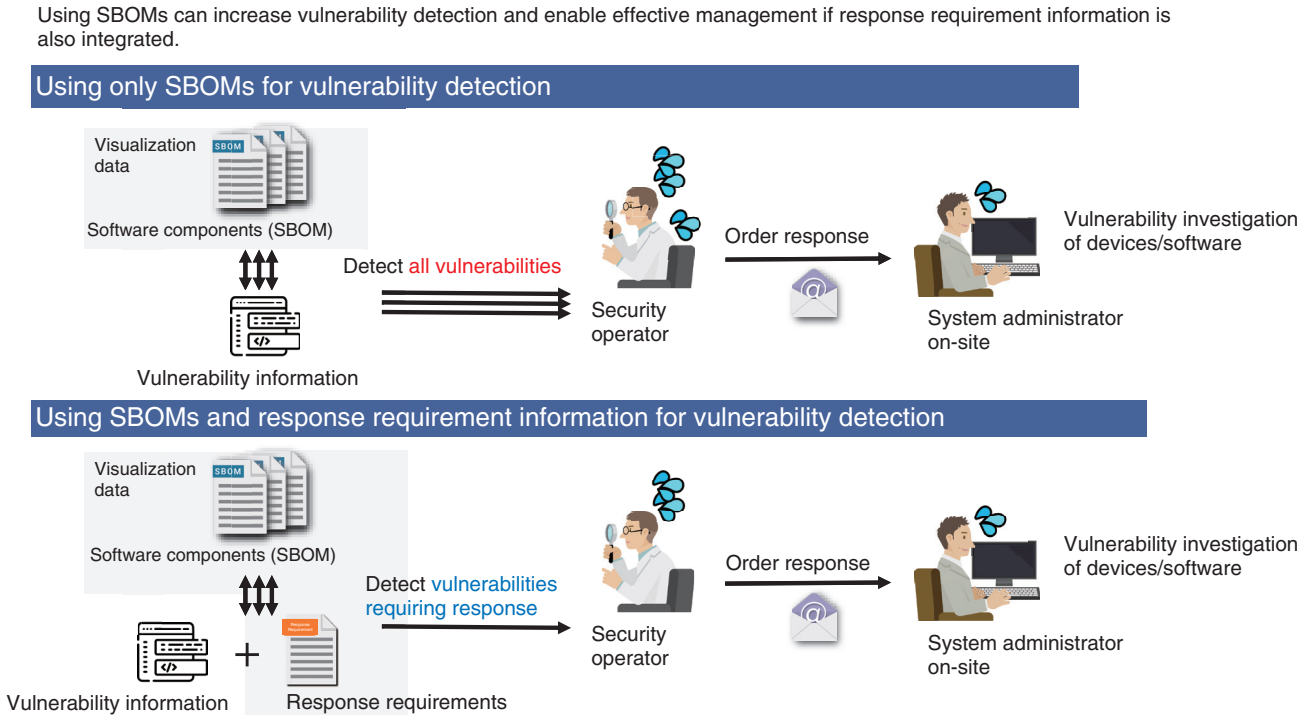

Fig. 3. Using vulnerability information as visualization data.

management, and security operators may need to gather additional information beyond the visualization data when required. In the collection of visualization data, there are elements that are exchanged between organizations and elements that are collected within an organization for use in vulnerability management.

Among the visualization data used for vulnerability response prioritization, information such as the security settings of the system on which the software operates or security control information from access control devices such as firewalls should not be shared externally to prevent leakage of sensitive information to attackers. Therefore, it is preferable to collect and use these data within the organization that uses the visualization data, rather than exchanging them between contracting organizations (companies).

Among the visualization data used for vulnerability response prioritization, vulnerability information investigated by the software product vendor is necessary for the organization using the software to conduct its own impact assessment. Therefore, this information should be disclosed externally in an appropriate manner. VEX falls under this category. One example under consideration is for software vendors to provide VEX information to a vulnerability database, enabling users to access the information through the database [8].

Among the visualization data used for vulnerability identification, information such as SBOMs should be exchanged between companies to confirm responsibility for vulnerability management within the supply chain. However, issues such as the increased workload for the vendor in verifying vulnerabilities and contractual models that arise from delivering or publishing SBOMs are still under discussion, and no unified policy has been established yet. Therefore, depending on the contracts and development models with suppliers, the first step toward efficient software vulnerability management is to establish a system within the organization that uses visualization data.

3. Conclusion

The use of visualization data, particularly SBOMs, is being widely discussed worldwide. Solutions for creating and managing SBOMs are also beginning to emerge. However, there are still many challenges regarding the distribution of SBOMs and visualization data within the supply chain from the perspective

of software vulnerability management. Issues, such as the lack of necessary information in SBOMs for vulnerability identification and the determination of appropriate indicators for vulnerability response prioritization, are still under consideration.

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Efforts to Improve and Utilize Security Transparency in Software Supply Chains

Yasunori Wada and Reika Arakawa

Abstract

Looking back on the expectations of various stakeholders for the utilization of visualization data to reduce risks in software supply chains and the actual situation in which the utilization has not progressed, we introduce the latest research trends toward addressing issues related to the use of visualization data and the security transparency technologies that NTT Social Informatics Laboratories is investigating.

Keywords: visualization data, SBOM, LLM

1. Introduction

In response to government trends in Japan and overseas, each business operator in a software supply chain is required to provide visualization data including a software bill of materials (SBOM) and respond to security issues. However, there are various practical and technical issues involved in the actual implementation of these measures. In this article, we introduce the issues that businesses face when responding to various systems, technical issues involved in the production and use of visualization data, and technologies that NTT Social Informatics Laboratories is investigating to expand the use of visualization data.

2. Expectations of various stakeholders

Institutions in the United States, the EU, and Japan require not only the provision of visualization data including SBOMs but also management of visualization data and vulnerability management using visualization data to reduce supply chain security risks.

However, from the perspective of each business operator in a supply chain, the requirements imposed by established systems and guidelines cannot be immediately reflected in system operations. For example, there are various tools and technologies for generating visualization data, and it is necessary to understand and select appropriate tools. Business operators will also need knowledge and best practices to manage and operate these tools. In accordance with the systems and guidelines of each country [1], the following issues need to be addressed.

First, there are issues in providing visualization data. Each business operator is required to provide an SBOM in various situations, but the content of the information and the format of data and files may differ depending on the requester. As we explain later, the same format contains different information. Business operators that generate visualization data need to select tools that meet these requirements and learn how to use them.

Next, there are issues related to operations using visualization data. Guidelines stipulate that an SBOM must be managed for a certain period, and it is also necessary to determine and manage the frequency of updating the SBOM, such as when updating software.

Security risk management using visualization data is also an issue. In addition to using visualization data to reduce security risks, each country's system requires business operators to certify compliance with security requirements, address vulnerabilities, and disclose information. Therefore, it is necessary for business operators to consider how to prove security using visualization data, what is disclosed, and

how to continuously ensure security using visualization data. To address these issues, it is important to cooperate between those who produce and use visualization data.

While the popularization of SBOMs has made it possible to identify software names and versions, it has been reported that attackers took the time to infiltrate the software development project and install a backdoor into the open source software (OSS) called XZ Utils that surfaced in March 2024 [2]. This suggests the new challenge of using visualization data not only to check whether suspicious software has been mixed in but also to check whether even legitimate software is operating illegally.

3. The status of visualization data

Software supply chains are formed through multiple different organizations and are becoming more complex. In addition, the reuse of OSS makes software security threats more serious. Visualization data are expected to contribute to increasing the transparency of software and as a means to combat these threats, but it is not yet fully utilized. This is due to various issues related to the visualization data.

The life cycle of visualization data is roughly divided into the generation phase, collection/management phase, and utilization phase, and there are issues with each phase. The generation phase is the phase in which users generate visualization data to manage device and system dependencies, licenses, and other configuration information. There are several issues with software configuration analysis (SCA) tools used to generate the visualization data. One is that the difference in the specifications of SCA tools causes inconsistency in representation in the character string output to the visualization data. For example, the difference between the prefix "Person:" and "Organization:" assigned by the SCA tool to the character string output as the organization name of the supplier and the difference between "organization-name inc" and "organization-name llc" are applicable. Each company has been addressing this issue, and some have implemented matching methods using their own databases [3]. There is another issue in that different SCA tools have different analysis performance. To give an example of our research data, we examined MongoDB image files from Docker Hub and found that the SCA tool Syft output 295 dependency packages, while Trivy output 136. The selection of an SCA tool is based on the configuration information to be visualized and the use of the tool according to the purpose. However, some research results suggest that there is no SCA tool that meets the minimum requirements [4] in the guidelines issued by the National Telecommunications and Information Administration (NTIA) in the United States [5, 6].

The collection/management phase collects and manages the generated visualization data. The issue is that it is difficult to handle the visualization data in a unified way because of the compatibility between them. There are two formats for visualization data, SPDX and CycloneDX. The former has many license information items and the latter has many security information items. When one manages collected visualization data, if one uses one of the two formats, the items will be insufficient. Therefore, it is important to consider a comprehensive format model and the development of an integrated platform to maintain compatibility [7].

In the final utilization phase, there is the security issue of sharing visualization data across different organizations. In other words, it is an issue of data integrity and access control to ensure that visualization data are not illegally rewritten in the process of sharing. To ensure the authenticity of visualization data, technologies that apply the verifiable credentials model in a blockchain to supply chains are being studied [8].

Issues related to visualization data differ depending on the phase, and there are both microscopic issues, such as inconsistent representation of visualization data, and macroscopic issues related to management and utilization of visualization data. Since these are no independent issues, it is difficult for a single company to address the issues that are barriers to penetration and utilization of visualization data. The direction of solutions by organizing various issues of visualization data has been discussed [9–11], but only a few papers have made technical proposals based on actual issues. In the Security Transparency Consortium, each company shares its knowledge and exchanges technical opinions for the popularization of visualization data.

4. Enhancing security operations using visualization data

Vulnerability management is a security operation that will be greatly changed by using visualization data. Vulnerability management involves the collection of vulnerability information, confirmation of vulnerability risks, and analysis of the impact on the organization [12].

The first step in vulnerability management is to understand the configuration of the hardware and software used by the organization. By accurately identifying the configuration, it makes it possible to accurately identify vulnerabilities. Examples of methods of identifying the configuration include the use of management sheets and package-management systems. Because the system configuration changes due to system updates, and some software is not managed by package management systems, these methods have problems such as omission of management and an increase in management operations. These problems can be solved by using visualization data to obtain accurate and up-to-date configuration information.

Other problems may arise. In vulnerability management, multiple pieces of information are used to analyze the impact of vulnerabilities. Examples include the severity of the vulnerability, availability of the exploit code, actual damage status, communication status, and process status. Because a security operator or developer uses these data to determine the impact, vulnerabilities can be accurately visualized and vulnerabilities that were overlooked in the past can be grasped; thus, vulnerabilities cannot be managed with the same approach as before. Therefore, along with research and development (R&D) on visualization data, R&D on vulnerability countermeasures is also required. The following are two such countermeasures.

The first is a technology that visualizes communication activities occurring in devices to narrow down the vulnerabilities that need to be addressed first. With this technology, information can be generated that is linked to the software information that made the communication. Therefore, information such as that software X version Y communicated with the global Internet protocol (IP) address Z can be visualized. Since communication information is information used to determine the impact of a vulnerability, it can be used to narrow down vulnerabilities that have a high risk and need to be addressed preferentially on the basis of the communication destination.

The second technology analyzes and visualizes programs that are executed when a device is started. This technology makes it possible to visualize the programs that are executed when a device starts up and those that are periodically executed. The information used to determine the impact of a vulnerability includes whether software is running, so it is possible to narrow down the software contained in a device that should be given priority during a vulnerability check.

We hope to advance the use of visualization data by developing technologies that solve the problems associated with the use of visualization data.

5. Initiatives to expand the use of visualization data

The device and system-configuration information described in the visualization data are mainly used for use cases of dependency understanding and vulnerability management. However, this is only an example of the use of visualization data alone. By using multiple sets of visualization data in a supply chain, more extensive use can be expected, such as identifying erroneous configuration information on the basis of the differences in configuration information among visualization data, or compensating for missing configuration information due to SCA performance based on the dependency and co-occurrence characteristics of configuration information. The characteristics of dependency and co-occurrence of configuration information means, for example, that if dependency package D is described in the visualization data and package D has a dependency relationship based on packages A and C, they have a co-occurrence relationship. We are building a platform to manage visualization data on a large scale and examining techniques to capture patterns by analyzing the characteristics of the configuration information as described above. We are also investigating techniques to estimate packages using large language models (LLMs) to supplement missing packages. We believe that these techniques will increase the value of the configuration information of the visualization data, contribute to the spread of visualization data in the future, and lead to the construction of a highly transparent software supply chain.

To further strengthen supply chain security, it is important not only to increase transparency and visualize risks as described above but also to appropriately deal with risks and use the experience for the next measures. In addition to visualization data, we are developing technologies to visualize risks in the development phase. We have established a source-code-dependency analysis technology that comprehensively detects risks by lexical string analysis. We are conducting technical verification of source code analysis using an LLM and aim to establish a new risk detection technology by semantically analyzing the processing content that was difficult with lexical features [13]. We are also investigating automated

vulnerability analysis and risk estimation, which require a high level of knowledge. This task is intertwined with the natural language processing of vulnerabilities, source code processing, analysis capabilities, and personal experience and knowledge. Therefore, it requires a high level of technology to automate. We are actively using LLMs that are strong in natural language and code analysis to break down tasks into smaller tasks and test their effectiveness. In the validation we conducted, we tested whether an LLM could identify whether a vulnerability was a triggered fix. The results of the validation indicate that the identification accuracy was somewhat high even with zero-shot prompts. However, the identification accuracy tended to be lower for vulnerability types with many vulnerability trigger points, making it difficult to treat all vulnerabilities in the same way [14]. Another study demonstrated that it is difficult to automatically fix vulnerabilities when the fixes exist across multiple files [15]. On the basis of these findings, we think it is important to properly decompose and examine the actual problem to determine the extent to which domain specialization is possible using an LLM. In the area of vulnerability, one specific technology cannot replace all other technologies. By conducting these studies and technical studies to ensure transparency through visualization data in both directions, gaps in the specifications and usage of each technology will be reduced, leading to the development of practical technologies to enhance the security of software supply chains.

6. Conclusion

This article introduced NTT Social Informatics Laboratories' research activities in the competitive domain based on social issues discussed in the collaborative domain of the Security Transparency Consortium. We will continue our research activities so that visualization data enable users to use software with confidence.

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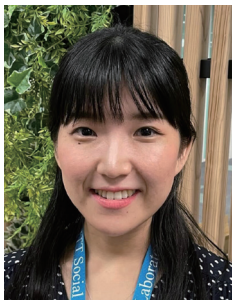

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Standardization Trends on QoE Evaluation in ITU-T Study Group 12

Masanori Koike, Noritsugu Egi, and Kazuhisa Yamagishi

Abstract

This article introduces recent standardization activities related to the evaluation of the quality of experience (QoE) of speech, audiovisual, and other new services such as object recognition for autonomous driving. The article focuses on the activities of the Study Group 12 of the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T SG12), which is responsible for standardization work on performance, quality of service, and QoE.

Keywords: ITU-T SG12, quality of experience, autonomous driving

1. ITU-T SG12

The Study Group 12 of the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T SG12) is the lead SG in ITU-T on quality of service (QoS) and quality of experience (QoE) in the worldwide standardization of media-quality evaluation that takes into account achievements in regional standardization bodies such as the European Telecommunications Standards Institute (ETSI) and Alliance for Telecommunications Industry Solutions (ATIS). Standardization work on network QoS is carried out in various standardization organizations such as the Internet Engineering Task Force (IETF) and 3rd Generation Partnership Project (3GPP). These organizations have confirmed that their work matches that of SG12.

2. Technologies for estimating effective equipment impairment factor for speech quality (Recommendation G.113, P.833.2, P.834)

Recommendation G.107 (E-model) has been standardized as a transmission-planning tool for Internet protocol (IP) telephony services and is used worldwide. SG12 has standardized Recommendation G.107.1 (Wideband (WB) E-model), which is a 100–7000 Hz speech-extension version of the E-model, and G.107.2 (Fullband (FB) E-model), which is a 50–14,000 Hz and 20–20,000 Hz speech-extension version of the E-model. In JJ-201.01 and JJ-201.11, which regulate the speech quality of IP telephony and IP mobile telephony in Japan, the speech quality is regulated using a rating factor *R*, which is calculated on the basis of the E-model, WB E-model, and FB E-model.

In E-model, WB E-model, and FB E-model, to calculate the effective equipment impairment factors (Ie,eff/Ie,eff,WB/Ie,eff,FB), which are intermediate parameters of *R*, equipment impairment factor *Ie* and packet-loss robustness factor *Bpl*, which are defined corresponding to the codec and bit rate in Recommendation G.113, are used. The *Ie* and *Bpl* for the LC3plus codec standardized by ETSI have been added to Recommendation G.113.

In the E-model and WB E-model, the methods for calculating the effective equipment impairment factor are specified in Recommendations P.833 and P.833.1, which are derived from the results of subjective quality-evaluation experiments, and Recommendations P. 834 and P.834.1, which are derived from the output results of an objective quality-evaluation model that estimates subjective quality by speech-signal analysis. With the standardization of Recommendation G.107.2, the FB E-model version of Recommendation P.833 had been studied and was standardized as a new Recommendation P.833.2. The FB E-model version of Recommendations P.834 and

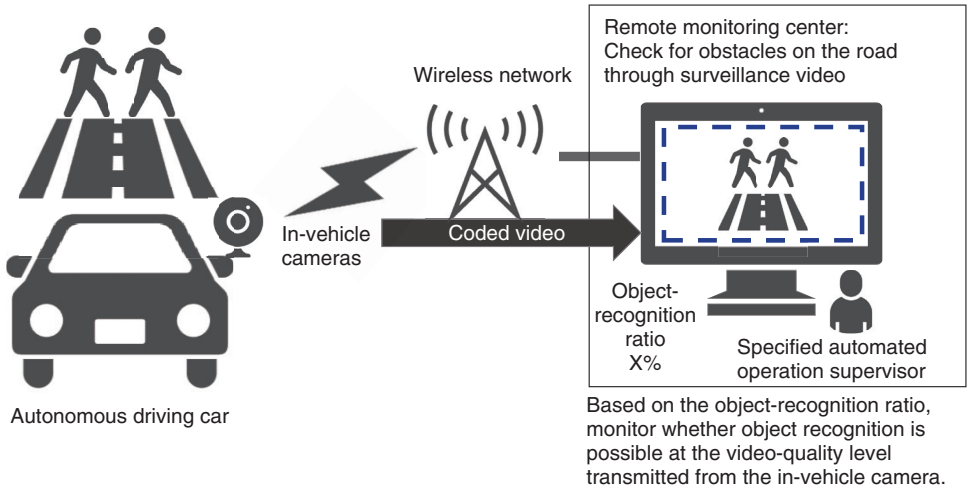

Fig. 1. Remote-monitoring-system configuration.

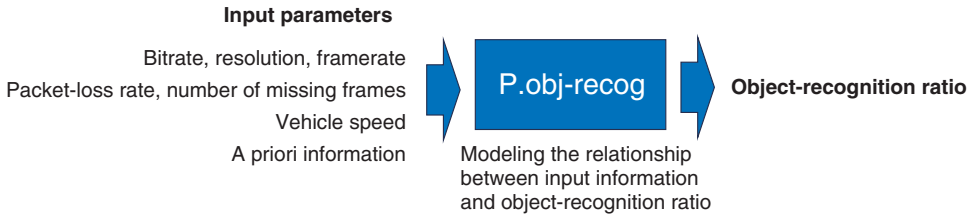

Fig. 2. Input/output of Recommendation P.obj-recog.

P.834.1 is also under study.

3. Object-recognition-rate-estimation model in surveillance video of autonomous driving (Recommendation P.obj-recog)

The Society of Automotive Engineers (SAE) has defined six levels of autonomous driving, Levels 0 to 5, depending on the driver and area where the autonomous car can be driven [1].

In autonomous driving without a driver (specified automated operation), which corresponds to Level 4, a remote monitoring center must be set, and a person who carries out remote monitoring (specified automated operation supervisor) must be assigned [2]. The specified automated operation supervisor checks for objects on the road on the basis of the video from the autonomous car's surveillance camera that is encoded and transmitted to the remote monitoring center.

Therefore, the quality of the videos transmitted from the autonomous car's surveillance camera must be clear enough for the specified automated operation supervisor to recognize objects. To confirm that the video is always clear enough for object recognition, a model to derive the probability that the specified automated operation supervisor can recognize an object from the encoded video has been studied, as shown in **Fig. 1**. This technique enables the monitoring of whether object recognition is possible at the video-quality level transmitted from the autonomous car's surveillance camera.

As shown in **Fig. 2**, parameters related to video encoding (bitrate, framerate, resolution), data loss during transmission (packet-loss rate, number of missing frames), and vehicle velocity are defined as inputs of the model, and the model outputs the object-recognition ratio. Since the quality of the video transmitted from the autonomous car's surveillance camera depends on day/night, weather conditions during operation, as well as surveillance camera settings, it is assumed that the coefficients in the estimation

technique are optimized for each of the a priori information. With this framework, we aim to establish a model that can respond to various situations expected in autonomous driving. At the most recent meeting, a test plan for obtaining the object-recognition ratio through subjective evaluation experiments was discussed, and the results of experiments conducted on the basis of this test plan were presented. After the model proposal is made, the accuracy of the object-recognition-ratio estimation for each model will be verified. This recommendation is scheduled to be established in 2025.

4. Future outlook

This article described subjective assessment and quality-estimation models for speech and object recognition for autonomous driving. SG12 has recently studied the extension of recommendations, such as revision of the FB E-model. A study on the quality of transmitted monitoring video for automated driving services has also been launched.

Since various services are expected to be launched along with the deployment of the fifth/sixth-generation mobile communication systems, the design and management of QoS/QoE for various services should be considered. Therefore, it will be important to investigate the activities of SG12.

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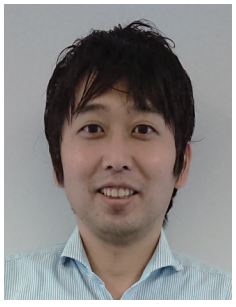

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He received a B.E. in electrical engineering from Tokyo University of Science in 2001 and M.E. and Ph.D. in electronics, information, and communication engineering from Waseda University, Tokyo, in 2003 and 2013. In 2003, he joined NTT, where he has been engaged in the development of objective quality-estimation models for multimedia telecommunications. He has been contributing to ITU-T SG12 since 2006. He has been a rapporteur of Question 13/12 since 2017, vice-chair of Working Party 3 in SG12 since 2021, and the vice-chair of SG12 for 2022–2024 Study Period.

External Awards

IPSJ Specially Selected Paper
Winners: Takuya Watanabe, NTT Social Informatics Laboratories; Eitaro Shioji, NTT Social Informatics Laboratories; Mitsuaki Akiyama, NTT Social Informatics Laboratories; Tatsuya Mori, Waseda University
Date: August 2, 2024
Organization: Information Processing Society of Japan (IPSJ)

For "Understanding the Breakdown of Same-origin Policies in Web Services That Rehost Websites."
Published as: T. Watanabe, E. Shioji, M. Akiyama, and T. Mori, "Understanding the Breakdown of Same-origin Policies in Web Services That Rehost Websites," Journal of Information Processing, Vol. 65, No. 9, 2024.

2024 PoC of the Year
Winners: Tomonori Takeda, NTT Network Service Systems Laboratories; Shin Kaneko, NTT Access Network Service Systems Laboratories; Kazuya Anazawa, NTT Network Innovation Laboratories; Hayato Ueda, NTT COMWARE Corporation
Date: September 3, 2024
Organization: IOWN Global Forum

For the achievement of a proof of concept of the Open All Photonics Network (APN).

ESA B best paper
Winners: Hideo Bannai, Tokyo Medical and Dental University; Mitsuru Funakoshi, NTT Communication Science Laboratories; Diptarama Hendrian, Tokyo Medical and Dental University; Myuji Matsuda, Tokyo Medical and Dental University; and Simon J. Puglisi, University of Helsinki
Date: September 4, 2024
Organization: 32nd Annual European Symposium on Algorithms (ESA 2024)

For "Height-bounded Lempel-Ziv Encodings."
Published as: H. Bannai, M. Funakoshi, D. Hendrian, M. Matsuda, and S. J. Puglisi, "Height-bounded Lempel-Ziv Encodings," ESA 2024, London, UK, Apr. 2024, Leibniz International Proceedings in Informatics (LIPIcs), Vol. 308, Article no. 18, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, 2024.

Communications Society: Distinguished Contributions Award
Winner: Kumi Jinzenji, NTT Software Innovation Center
Date: September 10, 2024
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Communications Society

For contribution as a secretary of the IEICE Technical Committee on Information Networks.

Communications Society: Distinguished Contributions Award
Winner: Noritsugu Egi, NTT Network Service Systems Laboratories
Date: September 10, 2024
Organization: IEICE Communications Society

For contribution as a secretary of the Technical Committee on Communication Quality.

Communications Society: Distinguished Contributions Award
Winner: Kazuhisa Yamagishi, NTT Network Service Systems Laboratories
Date: September 10, 2024
Organization: IEICE Communications Society

For contribution as an editor of IEICE Communications Society's English-language journals.

Communications Society: Distinguished Contributions Award
Winner: Yu Miyoshi, NTT Network Innovation Center/NTT Network Service Systems Laboratories
Date: September 10, 2024
Organization: IEICE Communications Society

For contribution as the vice chair of the Technical Committee on Information and Communication Management.

Communications Society: Distinguished Contributions Award
Winner: Yoshifumi Kato, NTT Network Innovation Center/NTT Network Service Systems Laboratories
Date: September 10, 2024
Organization: IEICE Communications Society

For contribution as a secretary of the Technical Committee on Information and Communication Management.

Communications Society: Distinguished Contributions Award
Winner: Atsushi Taniguchi, NTT Network Innovation Laboratories
Date: September 10, 2024
Organization: IEICE Communications Society

For contribution as a committee member of the Technical Committee on Communication Systems.

Papers Published in Technical Journals and Conference Proceedings

Change Point Detection Based on Cluster Transition Distributions

S. Takahashi, K. Takeshita, K. Yamagishi, and A. Shiozu

IEEE Access, Vol. 12, pp. 125145–125159, September 2024.

Nowadays, anomaly detection (AD) models are incorporated into various systems, but they will become useless if they are not updated (i.e., re-trained) to keep up with changes in their external environment. When trying to automatically trigger AD model updates in response to environmental changes, one promising solution is considered to be the use of a change point detection (CPD) method. Most existing methods impose stationary or independent and identically distributed (IID) constraints on the target time-series, and therefore are not suitable for our target time-series in telecommunications that often fluctuate periodically. In this paper, we propose a new clustering-based CPD method for detecting changes in non-stationary time-series. The proposed method enables pattern changes to be detected by tracking cluster transitions and calculating the distance between the cluster transition distributions for the past and current periods. The accuracy of the proposed CPD method itself and the effect of re-training the AD model at the detected change points are shown by using real hourly time-series data at mobile base stations in the Tokyo Metropolitan Area for nearly one year.

Strong Dipole-Dipole Interactions via Enhanced Light-matter Coupling in Composite Nanofiber Waveguides

K. Jain, L. Ruks, F. le Kien, and T. Busch

Physical Review Research, Vol. 6, 033311, September 2024

We study the interaction of emitters with a composite waveguide formed from two parallel optical nanofibers in regimes of experimental importance for atomic gases or solid-state emitters. Using the exact dyadic Green's function we comprehensively investigate the coupling efficiency and the fiber-induced Lamb shift accounting for variations in emitter positions and fiber configurations. This reveals coupling efficiencies and Purcell factors that are enhanced considerably beyond those using a single fiber waveguide, and robustness in the figures of merit. We finally investigate resonant dipole-dipole interactions and the generation of entanglement between two emitters mediated through the composite waveguide under excitation. We show that the concurrence can be enhanced for two fiber systems, such that entanglement may be present even in cases where it is zero for a single fiber. All-fiber systems are simple in construction and benefit from a wealth of existing telecommunications technologies, while enjoying strong couplings to emitters and offering interesting light-matter functionalities specific to slot waveguides.