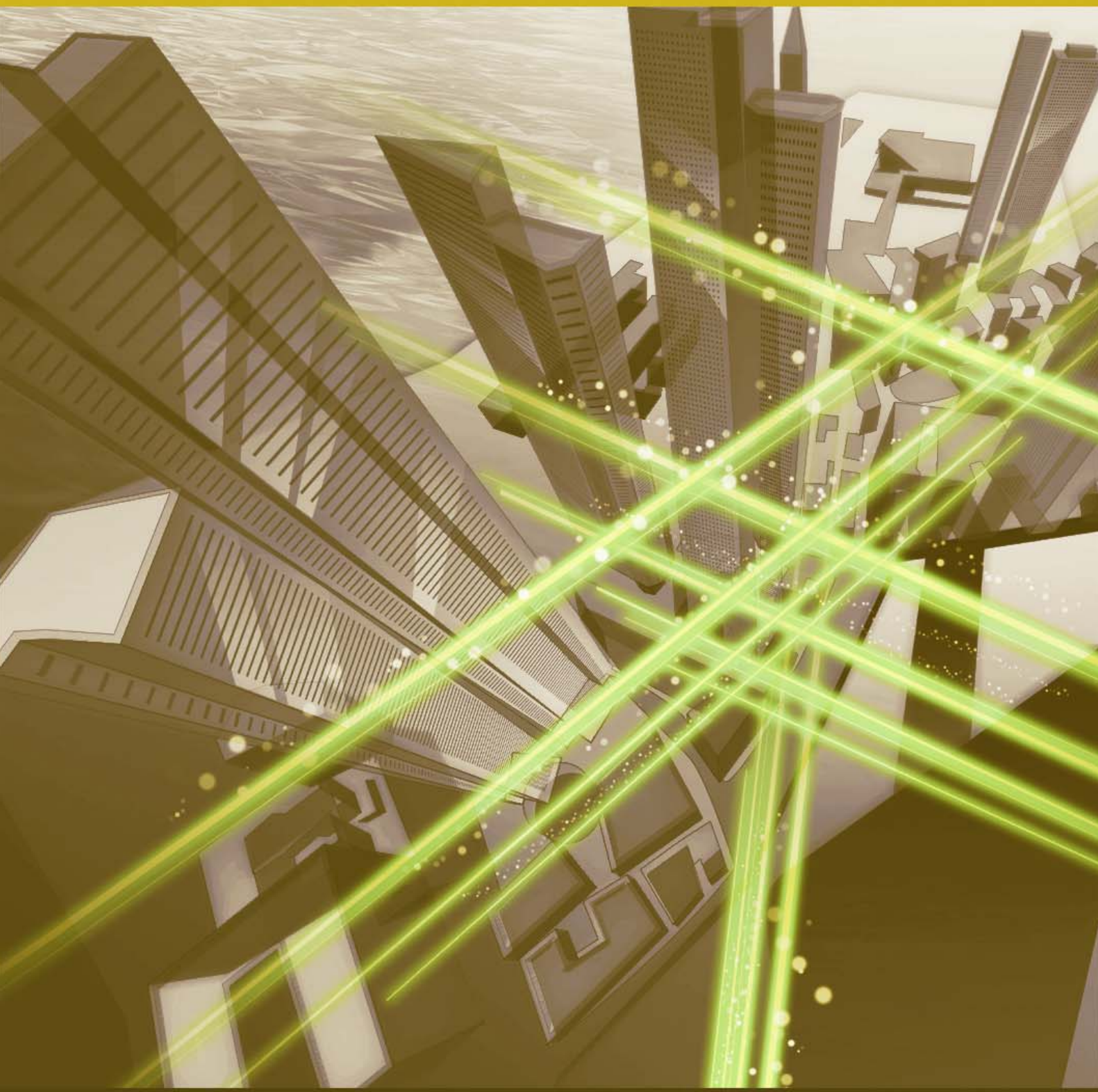
NTT Technical Review

7
2021



July 2021 Vol. 19 No. 7

NTT Technical Review

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Creating a Communication-rich Environment by Making the Most of Researchers' Diverse Personalities

Tetsuomi Sogawa
Senior Vice President, Head of NTT Science and Core Technology Laboratory Group

Overview

The NTT Science and Core Technology Laboratory Group is engaged in research and development with the following three missions: "Research and development of cutting-edge technologies to expand NTT's business domains," "Creation of new principles and concepts that will revolutionize society," and "Research and development of technologies that are friendly to the global environment and people." To contribute to society, the laboratory group is creating new values through the results of its research while keeping an eye on current trends. We interviewed Tetsuomi Sogawa, senior vice president, head of the NTT Science and Core Technology Laboratory Group, about the social mission of the laboratory group and mindset required for researchers to lead the world.

Keywords: NTT Science and Core Technology Laboratory Group, R&D, IOWN

Researchers, sharpen your saws!

—Please tell us about the vision and social mission of the NTT Science and Core Technology Laboratory Group.

The NTT Science and Core Technology Laboratory Group is conducting a wide range of research and development (R&D)—from basics to applications—while always looking at how to create a future with technologies. Specifically, we are focusing on information-processing and communication technologies with the highest performance in the world, sustainable technologies that enable the creation of new value through innovative ideas, and human science and biotechnology that deepen the understanding of humans. By achieving world-best, world-first technologies or creating amazing technologies, we aim to strengthen the competitiveness of the NTT Group while making the concept of the Innovative Optical and Wireless Network (IOWN) a reality.

The NTT Science and Core Technology Laboratory Group consists of four laboratories: the Network Innovation Laboratories, Device Technology Laboratories, Communication Science Laboratories, and Basic Research Laboratories. The Network Innovation Laboratories is researching and developing budding technologies that will expand the world's highest-level optical- and wireless-communication capacity and area coverage. The Device Technology Laboratories is researching and developing devices and materials that will create new value. To make

innovative technologies available to a wide range of industries seamlessly, the Device Technology Laboratories is working closely with the Device Innovation Center, which is in charge of device development at the IOWN Integrated Innovation Center. The Communication Science Laboratories researches media, information processing, and human sciences to enable communication that *reaches the heart*, and the Basic Research Laboratories researches materials science, electronic physical properties, and optical physical properties for creating new principles and concepts that break the limits of network technology.

In the mid-1980s, Japanese companies established basic and central research laboratories one after another. However, after Japan's bubble economy burst, those companies began to cease these activities, and the number of existing basic research labs is very small. Since it is extremely difficult to renew social infrastructure once it was constructed, corporate research labs are required to create technology with a bird's-eye view of the future. To bring better technology to the world, we regard researching from theories and basic principles of things as important, and this stance is one of our strengths.

—It has been reported that in Japan, researchers are not as highly evaluated as researchers in the rest of the world and that research funding is low.

That is a difficult issue. For example, a smartphone contains a processor equivalent to a supercomputer of the past. Unfortunately, the efforts of the researchers who made it possible have been hidden behind the impact of the product, and they are not well known. Researchers may not be good at telling people about the fruits of their challenging research results; even so, the tasks that research labs and researchers have to perform differ from those they had to perform a while ago, and one of those tasks is to convey the significance of their research.

We must recognize that this task is a much tougher challenge than we imagined. World's-first achievements do not always provide the highest quality, and since they are new, people cannot comprehend them well. Consequently, when we talk to someone about such achievements, we almost always get a negative reaction. We can gain their cooperation only after we convince ourselves that our research is superior and continue to explain it to those around us.

When I was the vice president, head of the Basic Research Laboratories, we tried to give easy-to-understand explanations to journalists when we made a press release; however, they were still difficult to understand. Therefore, we used a live-streaming service called "Niconico Live" to convey the significance of our research to a general audience and answered questions from them. I think it was a good endeavor because researchers came to better understand the essence of their research by repeatedly explaining them in the live-streaming service.

In the days when Japan was simply following the research of other countries, we knew what needed to

be researched. All we had to do was increase the performance of products through continuous improvements. However, Japan has become one of the top countries of scientific research and is in a position to provide guidance on research. Our role is to set the rules for what problems should be solved and themes to be tackled in the next generation. In other words, we are expected to not only solve the problems for continuous improvement but also make breakthroughs. However, I feel that Japanese researchers are still not very good at meeting such expectations. Although it is very difficult to identify the next generation of research problems, as a starting point, it is important to review the problems we are working on from a different perspective. Therefore, I often tell researchers, "Sharpen your saws!" There is a story of the woodcutter's dilemma, in which the woodcutter would eventually cut trees using his dull saw if he spends a lot of time doing so, but if he paused and sharpened his saw, he would have cut them more efficiently. If we can apply this story in our research and successfully "sharpen our saws," we can discover new solutions to the problems we are currently facing. Moreover, by comparing our perspectives with global trends and taking a bird's-eye view of things, we may be able to find new themes and solutions to be tackled.

Having an optimistic mindset is necessary when conducting basic and cutting-edge research

—Do you have any tips for making breakthroughs?

NTT R&D has a long history of conducting meetings and conferences implemented for the next generation of researchers. For example, in 2000, when I was working in the planning department of the Basic Research Laboratories, we introduced an advisory board. It is unusual for a research lab of a private company to ask for external evaluation; regardless, we had doubts about evaluating the value of NTT R&D solely on our own. Therefore, to borrow the wisdom of experts from overseas, thus advance research that would contribute to future communications and information processing, we launched the advisory board under the leadership of the vice president, head of the Basic Research Laboratories. I was a visiting researcher at the Paul Drude Institute in Germany, so I contacted a professor who was active in Europe in fields relatively close to mine. In the advisory board, for example, it was pointed out that we should focus not only on themes related to superconductivity technologies that will enable quantum computers but also on photonics technologies that will lead to quantum communications, which prompted us to review our research portfolio. The advisory board has been held every two years for more than 20 years, and the board members include Nobel laureates and former chairs of the Nobel-laureate selection committee. The establishment of new job titles such as fellows and senior distinguished researchers was also based on advice from the board, and it has provided researchers with the motivation for working at NTT for a longer time.

The BRL (Basic Research Laboratories) School is another initiative taken at the Basic Research Laboratories. The school invites overseas graduate students and postdoctoral researchers, as well as

lecturers from Japan and abroad, to foster the next generation of researchers through lectures and discussions. Various summer schools are held in Europe, creating a cycle in which the students who study at such schools become faculty members at universities then become lecturers at later summer schools. I believe that such efforts are indispensable for NTT R&D. In fact, a postdoctoral researcher who participated in the first BRL School is now a professor at a European university and has sent interns to work with us at NTT. It can be geographically difficult to work closely with research communities far from Japan, but that is not a problem as long as we can build a trusting relationship with them. Since what we can do alone is limited, we would like to build relationships in which researchers around the world can bring their strengths to the table. It is therefore unfortunate that most international conferences are currently held online due to the COVID-19 pandemic and we cannot present our research or visit laboratories overseas. Online conferences are different from physical ones in terms of being fully stimulated. By visiting various sites and meetings and talking face to face with various people, we often find new things that we were not aware of until then.

—It seems that the stimulation you receive in person is very important.

When I was discussing the ultrasonic waves that were used to transport electrons in semiconductors in Germany, researchers told me that NTT had used ultrasonic waves for optical communications in the past. They review an old technology and apply it to electron transport on semiconductor surfaces, and in doing so, they created a new function. That discussion led me to the idea of transport of electron spins—which I was studying at the time—in semiconductors, and after returning to Japan, I continued to work on that research theme while having regular discussions with my German peers. This theme has evolved into research on controlling the state of electron spins in semiconductors and extending their lifetime, and such research has been continuing at the Basic Research Laboratories.

In basic and cutting-edge research, we cannot easily achieve good results. Achieving success once a year is regarded as great performance. In fact, most of the research is a series of failures. To face that reality, we need to have an optimistic mindset. There are two types of optimistic people: the “definitely optimistic,” who face situations with confidence, and the “indefinitely optimistic,” who face situations without much evidence to support that mindset. The German researchers that I worked with were definitely optimistic, and they proceed with research on the basis of theories and prospects. In actual research, it is more likely that things will go wrong even when we are confident. When that happens, it is important to compare our experimental results with theories again and change the course of our hypothesis.

Certain words and phrases have inspired me. I have had several opportunities to talk with Nobel Laureate Dr. Leo Esaki ever since I was a doctoral student, and

he valued the phrase "Think the unthinkable." He said to me, "You are young, so think the unthinkable. As we age and make mistakes, we gradually develop a judicious mind, but lose our creative mind." Another phrase that inspired me is "Zero to One," the title of a book by American entrepreneur Peter Thiel. This phrase, which means "creating something from nothing" is another way of expressing the mission of our laboratory group. We will keep these phrases in mind as we continue to take on a variety of challenges to bring innovation.

The job of a manager is to build and protect the environment for innovation. We are trying to create an environment in which rules are kept to a minimum so that researchers can do their research activities freely and their supervisors can support them, which enables us to make the most of their diverse personalities. We believe that this is the best way to achieve results at our group. In particular, if we make researchers think too much about commercial applications of their research results, their ideas will become limited; therefore, I would like to leave concern about applications to someone who has a different role and let our researchers simply focus on achieving interesting results.

The real pleasure of management is when researchers go through a significant transformation

—You are a researcher, but now you are in a management position. I think many people want to continue their research activities at the forefront. What is the significance of appointing a researcher as a manager?

Since I joined the company as a doctoral graduate, I thought I'd continue in research for a long time, but now I am in a management position. However, even if I stayed at the university and became a researcher, I would have eventually become a faculty member, and half of my work would have been management, so I think I've ended up in the same situation in the end.

Managers in research laboratories evaluate people who are producing research results at the forefront, so they must be acceptable to the people they evaluate. In addition, the intuition of a researcher is important for being managers in research laboratories when making decisions about the direction of the research. In other words, it is necessary to have deep insights and have the skills to convince others. Some people think that management activities are separate from research activities; on the contrary, I believe that the two activities are closely connected because management activities help us organize our research activities.

When I was the vice president, head of the Basic Research Laboratories, I was not in a position to research at the forefront. Therefore, I wrote papers on the basis of my own past experimental data. Naturally, I don't write papers now as a first author but I have been a joint author on several papers, so I continue to discuss research with frontline researchers. It is unfortunate that I have little time to be involved in research and writing papers; however, many people are conducting outstanding research, and I believe that my current job is to encourage them. I am impressed when I see an ingenious approach that differs from my own ideas.

When researchers go through a significant transformation, I feel the real pleasure of R&D management. As researchers change themes and accumulate various experiences, they sometimes grow rapidly toward their next step. I am happiest when researchers express their viewpoints and show me results that are beyond what I had expected.

The concept of IOWN proposed by NTT R&D and one of its components, the All-Photonics Network, is a vision that meets the long-term goal of our laboratory group. What I had set out to do 30 years ago when I was a fledgling researcher is starting to look like a reality. Therefore, I believe it is important to start planning our next initiatives now by looking ahead 30 years from now. By steering the ship so that it does not drift in the wrong direction, we at the NTT Science and Core Technology Laboratory Group would like to take a leadership role in the world by working with researchers to come up with ideas and provide a roadmap to achieve them.

—What would you like to say to the researchers and engineers inside and outside the company?

The creation of new technologies and innovations is essential for Japan to survive. I hope that researchers and engineers will continue to play their role with that mission in mind. Japan's technological capabilities have always been high, but I feel that Japanese researchers are not good at creating rules and becoming leaders of trends. To increase our research and technological capabilities, let's set our direction and show a vision to stay on top of the world.

Japanese researchers are very talented, but in the past, many seemed shy and not good at asserting

themselves. However, the younger generation has changed quite a bit. At international conferences, I often see young researchers get the most out of their participation; they try to learn about fields other than their own and obtain knowledge by actively asking questions. They look confident and have a promising future. The battle for technological supremacy is extremely fierce, so let's regain our spirit and liven up Japan.

Interviewee profile

■ Career highlights

Tetsuomi Sogawa joined NTT Basic Research Laboratories in 1991. From 1999 to 2000, he was a guest scientist at Paul Drude Institute in Berlin, Germany, where he investigated acoustic spin transport phenomena in semiconductor quantum structures. From 2004 to 2006, he worked for the Council for Science and Technology Policy, Cabinet Office, Japan, as a deputy director for policy planning. He became senior research scientist at NTT Basic Research Laboratories in 2006; executive manager of Research Planning Section, NTT Science and Core Technology Laboratory Group, in 2007; group leader of Quantum Optical Physics Research Group, NTT Basic Research Laboratories, in 2010; executive manager of Optical Science Laboratory, NTT Basic Research Laboratories, in 2012; and the vice president, head of NTT Basic Research Laboratories in 2013. He has been in his current position since June 2018.

Pursuing Research with the Attitude that "Fortune Is Unpredictable and Changeable" and Building Relationships to Inspire Each Other

Masayuki Abe
Senior Distinguished Researcher,
NTT Secure Platform Laboratories

Overview

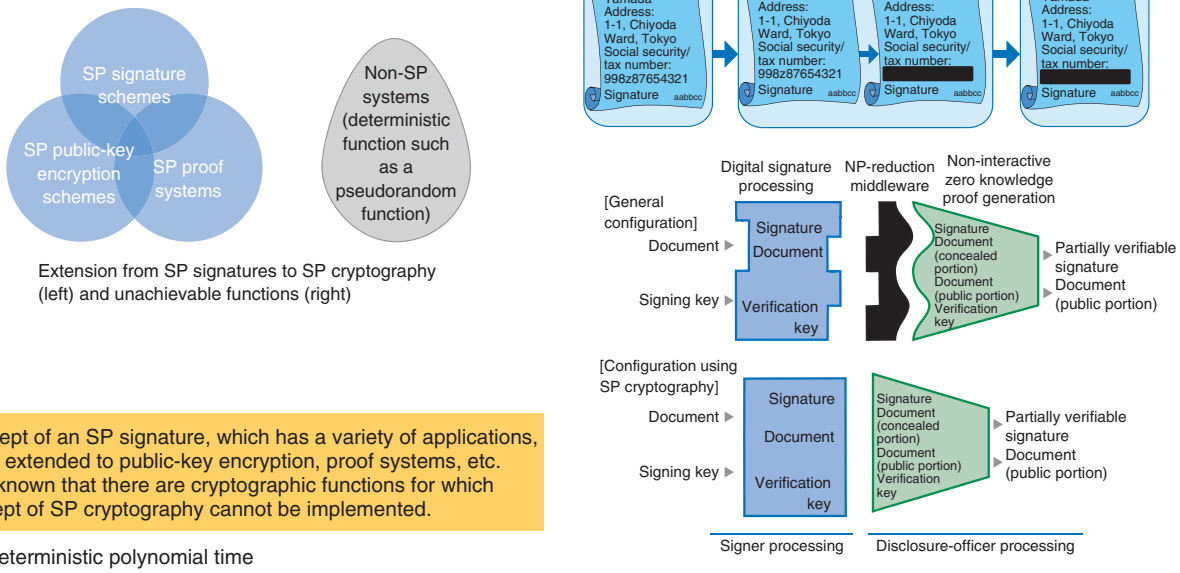
E-commerce transactions using electronic payments and e-government functions, such as online tax filing, continue to expand. Amid this trend, modern cryptography is being actively researched and developed as a technology for guaranteeing the safety of networks and services. Masayuki Abe, a senior distinguished researcher at NTT Secure Platform Laboratories, is known for his pioneering research and creation and implementation of many innovative technologies in cryptography. In 2018, he received the Maejima Hisoka Award, which is presented to individuals for their outstanding achievements in the fields of information communications and broadcasting. We asked him about the current state of his research and the role of a researcher.

Keywords: cryptographic protocol, structure-preserving cryptography, quasi-adaptive non-interactive zero-knowledge proof, smart contract

Clarifying "what can't be done"

—Dr. Abe, please tell us about the research you have been involved in since our last interview.

The main theme that I have been pursuing is the composing of secure cryptographic protocols. The process of safely delivering only the information needed to parties in need of it by encrypting the original information and attaching a digital signature is called a cryptographic protocol, and developing an approach toward a safe and efficient cryptographic protocol is my ultimate objective. A cryptographic protocol is a combination of diverse elements in a multilayer configuration, so the targets of research span a wide range from basic to applied. The basic components of a cryptographic protocol change through tuning in parallel with technological advances. This is truly a matter of technical craftsmanship. However, technology lying above these basic components can handle changes due to technological advances by combining existing technology with new technology because basic components absorb such changes. In such a complex system, I try to develop



Extension from SP signatures to SP cryptography (left) and unachievable functions (right)

The concept of an SP signature, which has a variety of applications, has been extended to public-key encryption, proof systems, etc. It is also known that there are cryptographic functions for which the concept of SP cryptography cannot be implemented.

NP: non-deterministic polynomial time

Fig. 1. SP cryptography.

both comprehensive solutions and solutions to specific problems in a balanced manner.

Since the last interview in 2013, I have been involved in three major research themes. The first is proving that there are unfeasible functions in structure-preserving (SP) cryptography (**Fig. 1**). SP cryptography achieves a high degree of safety by combining multiple cryptographic technologies via a uniform interface. This concept is being widely used, but it has been found that there are cryptographic functions for which this concept cannot be implemented, so I would like to explain and prove this. The second theme is proving non-composability (**Fig. 2**). I would like to prove that when composing an advanced function by combining multiple functions in SP cryptography, using only the interface of a certain function does not make it possible to compose a desired function. Finally, the third theme is studying a system for the safe buying and selling of information using smart contracts from basic research to actual applications (**Fig. 3**).

The idea of SP cryptography came to me around the end of 2009, and 2013 (when the last interview was conducted) was the year that I developed an SP digital signature and came closer to making it a reality. Through joint research conducted with Karlsruhe Institute of Technology (KIT) in Germany, we developed the world's first highly safe and interoperable SP digital signature scheme. We presented this achievement at CRYPTO 2017, a leading conference sponsored by the International Association for Cryptologic Research, held in the United States in August 2017 [1, 2]. Following this, I continued to pursue the arrangement of interfaces for cryptographic functions other than digital signatures and began the development of quasi-adaptive non-interactive zero-knowledge proof (QA-NIZK) systems. Through the development process of QA-NIZK systems, I explored not just combinations of interfaces but also functions and clarified limiting points at which safety could not be guaranteed. In other words, we clarified "what can't be done." This achievement brought us recognition in the field of cryptography and enabled us to create a new research area.

—How important it is to prove limiting points and impossibilities concerning cryptography?

At first glance, it might appear that proving an impossibility is not productive, but knowing what is not possible is very meaningful. In the research on cryptography, changes in computer technology bring

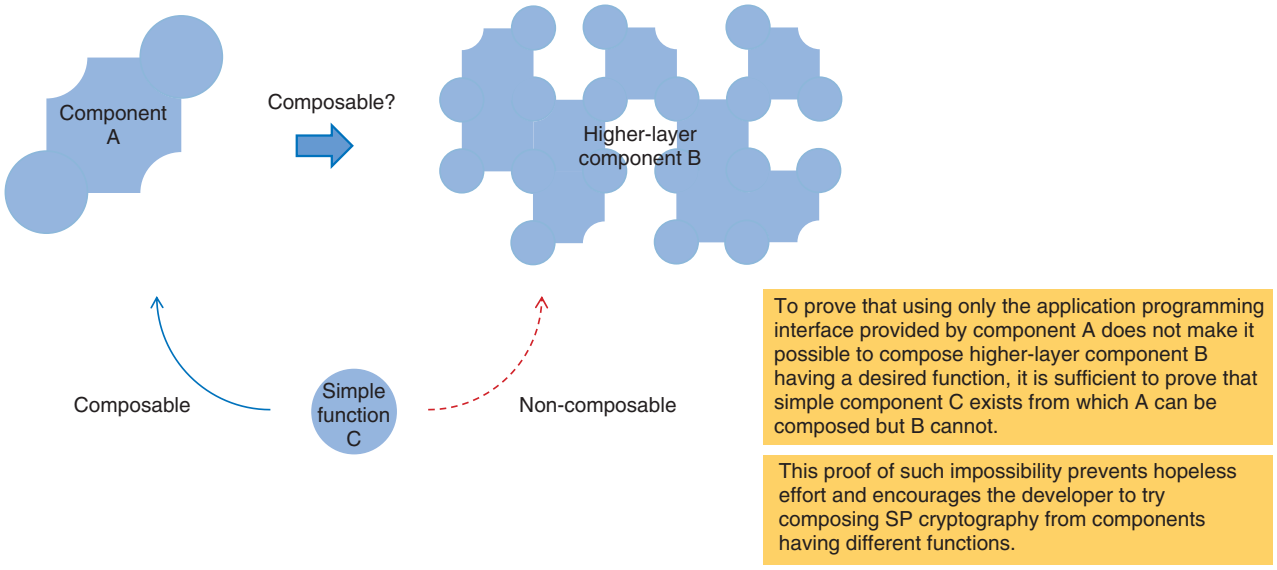


Fig. 2. Proof of non-composability.

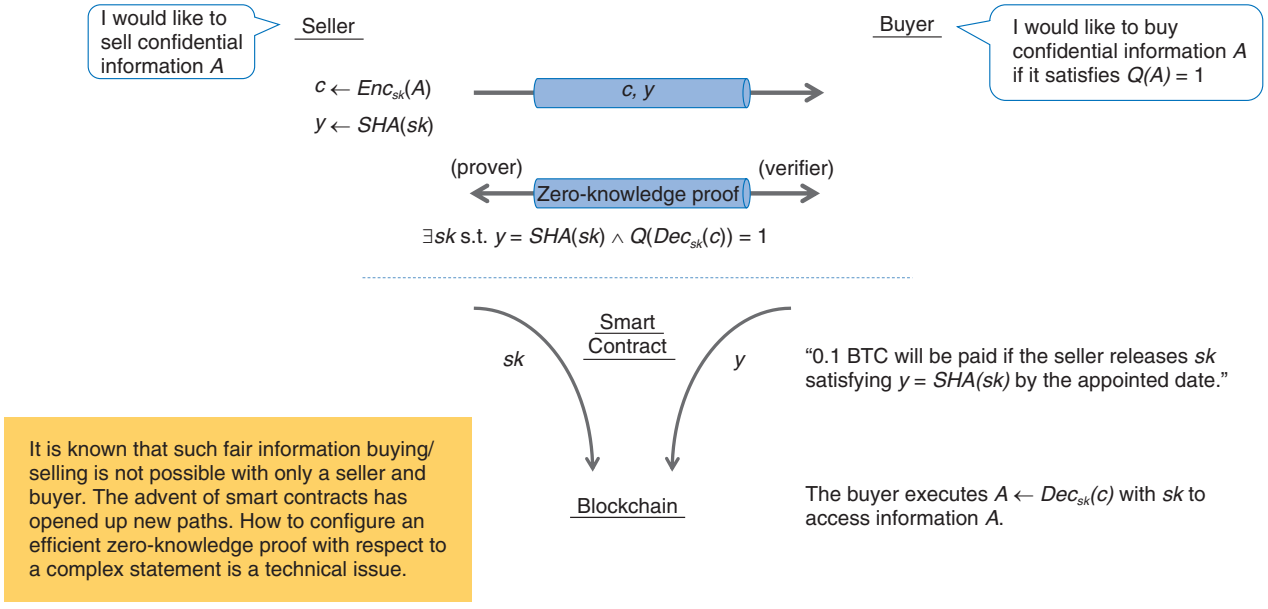


Fig. 3. Safe information buying/selling using blockchain-based smart contracts.

about changes in the level of attackers, which means changes in the concept of safety. Simply put, to ensure that the safety of the foundation of computers does not impact the technologies built on top of it, it is necessary to understand the limiting point of that impact. Proving an impossibility is an action that tells us "road closed from here on" and teaches us the nature of what is impossible. It is therefore extremely meaningful research that can lead to new methods of constructing cryptographic protocols.

I first began to use such a research approach (proving limiting points and impossibilities) for exploring the language extension of non-interactive proof systems. A non-interactive proof system is a technology

that completes a proof by simply sending information in a one-way manner. It is a cryptographic technology different from digital signatures, but I also pursued the limitations of this technology. As an example of non-interactive proof systems, we can take the case of verifying an individual's age. This can be accomplished, of course, by asking the individual in question to present a medium (such as a driver's license or passport) on which personal information including birthdate has been inscribed. However, if the individual does not want birthdate or other personal information to be referenced, this problem can be solved if it was possible to present only one's age. The technology that makes this possible is zero-knowledge proofs in a field of cryptography called proof systems. Non-interactive proof systems have good affinity with SP cryptography, and they have been used in combination. I considered that using them in combination could prove an even greater set of facts. For example, I began to investigate an extension to proof systems that would enable the proving of a composite situation such as being 20 years or older, possessing a driver's license, and working for a company with 2000 or more employees. However, I understood this to be difficult, and I'm currently trying to clarify whether it's simply difficult or just impossible.

In the research of cryptography, thinking about safety tailored to individual requirements is necessary. One part of this work is to determine to what point protection can be provided by cryptographic theory and to clearly identify the "protect surface." A researcher studies the meaning of safety and the use of a cryptographic technology every time such new technology has emerged. For example, a smart contract facilitates the automated execution of a contract by applying the technology of non-interactive proofs to support blockchains. In the beginning, this technology was not very efficient, and its safety could not be clearly shown. I first attempted to address these technical issues in application systems and in the field of blockchains together with a postdoc (a person working at a research organization for a fixed term after obtaining a doctor's degree) from Europe, and we were able to propose a method for the safe selling and buying of digital information. There is still much to be studied in this area, and I would like to continue my research on this technology.

Linking up with people leads to achieving research results

—Is there anything that you keep in mind to enrich your research activities?

At one time, the research field of cryptographic protocols was made up of a relatively small community of researchers, and research targets were limited. However, concepts of information security have become widely acknowledged and the range of its research has broadened, so I sometimes could not fully follow discussions in neighboring fields in adjacent sessions at academic conferences.

What helps me in such situations is to broaden my perspectives and interact with coauthors of past papers or with friends and acquaintances. It is very difficult to collect information and accomplish research on one's own, but one can acquire new information by communicating with people one knows.

My research of smart contracts that I mentioned above is a good example of this practice. What started me off in this research was a conversation with a postdoc who went on to achieve good results in this field and become a fellow researcher. As a result of that interaction, I went on to pursue smart contracts in earnest and write impactful papers. I first encountered him at an academic conference held in Spain. At that time, he was still a student, but he gave a presentation on a research theme that I had worked on in the past. I thought it was a very interesting presentation, and I called out to him saying "Good presentation!" and talked with him for a while. No more came of this chat at that time, but several years later, he contacted me saying "I'm going to complete graduate school soon and would like to do some research under you." That was the beginning of our research collaboration. I think that this collaboration would have never happened without that one face-to-face conversation.

This experience taught me that networking with people is of great value to researchers, and I have since placed much importance on relationships with friends and acquaintances. I make an effort to go out and meet a variety of people whenever an opportunity arises, such as a conference, and connect such interaction to research. I have been doing this for quite some time, so I now have many friends and acquaintances who are in authoritative positions, which has given me the opportunity to make connections with some of their students. In this way, I have been able to form good connections from which new research activities are born. I take great delight in the fact that

linking up with people leads to achieving research results.

—Such fulfilling connections certainly have a great impact on research. What types of researchers do people tend to gather around?

People naturally gravitate towards researchers who have extensive knowledge about topics one doesn't know about. Of course, it's important to be such a knowledgeable person, but since research activities include relationships between people "living under the same roof," it is even better to connect with people with whom you can get along.

Young researchers may connect with each other in a more systematic manner, but I want to place priority on connecting with the human side of research. This is because research, for me, is a part of life, and most of my life has been made up of research activities. There is no way that I would like to detach myself from something that I feel to be so important.

Basically, research requires output, so input becomes important in creating that output. Where that input comes from, such as human relationships or leisure activities, depends on the person, but I obtain input from my worldwide connections with people. I have been very fortunate in being in an environment in which I can leverage these relationships to enrich my research activities.

However, the COVID-19 pandemic of 2020 prevented me from building such personal connections. The Great East Japan Earthquake of 2011 interrupted my linking up with people in the same way. At that time, postdocs who had planned on joining my research group were hesitant about coming to Japan because of this disaster. I was able to gradually eliminate their fears by convincing them that Japan was safe, but this worldwide COVID-19 outbreak has presented a different set of problems. This time, we too cannot venture overseas, and it's difficult for overseas researchers to come to Japan. There are researchers of foreign nationalities living in Japan, but there are very few researchers who would like to try to come to Japan at this time. Although we can connect remotely with people we already know and can make new acquaintances through their introductions, it's unfortunate that unexpected encounters cannot spontaneously occur.

Words of encouragement to young researchers provides encouragement for oneself too

—As a pioneer in the field of cryptography, how do you view the development of this field?

The field of cryptography has matured thanks to an accumulation of achievements since 1970. Many young researchers have entered this field and pursued wide-ranging research, which has broadened this field. I believe that the process in which a technology matures is not simply an accumulation of core components but also the ongoing formation of a broad base, much like the shape formed by picking up a bed sheet with one's fingers. The searching out of all sorts of possibilities by many researchers broadens this field in the lateral direction while pursuing cutting-edge research extends the field in the vertical direction. The fact that this shape does not collapse reflects the maturity of this research field.

In the field of cryptography, there was a time when new ideas were announced at a fervent pace, but today, the broad base of this field means that new ideas must be discussed after giving sufficient consideration to peripheral areas. Moreover, papers of about 10 pages in length would have been accepted in the past, but papers of 30 to 40 pages in length have become the norm, making it all the more difficult to complete a paper. At the same time, the development of cryptography into a broad-based field such that one does not know what neighboring researchers are working on means that each researcher has worked their utmost to succeed, thereby raising the possibility of becoming the one and only in one's field of study, which can be very gratifying.

Yet, in any research field, a technical revolution in basic components increases the possibility of having to reset research up to that point. For example, the crossbar switch in communication networks was replaced with the digital switch, which was replaced with the router. Therefore, past technologies have been replaced with technologies based on completely different concepts. Similarly, fields that are close to the basic components of cryptography have been evolving. Computers, which have a close relationship with cryptography, are now on the verge of entering the quantum computer era after making great progress from the era of vacuum tubes. The time has come to construct cryptographic protocols that can deal with quantum computers, which will break down cryptography based on conventional mathematics. To keep up with this development, researchers have to be

adept at completely new technologies. On the other hand, cryptographic protocols that I am pursuing are well positioned for use in application fields, so I think I can make use of my knowledge to date.

—Dr. Abe, what do you think is the role of a researcher and what advice would you give your junior researchers?

Much like organisms in the natural world, researchers have completely different personalities with each having meaning and a role to play in an ecosystem that they called a research community. If the characteristics of researchers were to be uniform, I don't think there would be anyone to be inspired by and I don't think that anything original would be developed. In other words, stimuli (expertness, achievements, etc.) among fellow researchers influence each other and ignite something (research) that each researcher has been working on.

I would like all young researchers not to forget to give things time. When giving and taking knowledge, there is no need to repay a debt immediately, to think with a short-term, narrow field of vision, or to make decisions hastily. There is a proverb that I like, "fortune is unpredictable and changeable," which I think can be interpreted in various ways. I take it to mean, "think with a long-term view." I think it's best to make decisions by adopting long-term and broad perspectives.

To be honest, having to reset the knowledge that one has accumulated due to technical innovations and the coming of a generational change can be quite distressing. One part of the work of an NTT senior distinguished researcher is to train the next-generation of researchers and give them opportunities, and I'm quite pleased to see young researchers continuously putting out results and building relationships. A senior distinguished researcher is also expected to be an active researcher, so I need to keep up with the results presented by young researchers. When I observe the activities of young researchers, I sometimes worry, "Will I really be able to keep up with them?" But even without going head-to-head with young researchers to prove myself, I feel that I can overcome my concerns and remain active as long as the research that I am working on matches well with current needs and interests. I believe that the words that I use to encourage young researchers encourage me as well! Going forward, I have no intention of resting on my laurels—I want to keep challenging myself.

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■ **Interviewee profile**
Masayuki Abe

Senior Distinguished Researcher, NTT Secure Platform Laboratories.

He received a Ph.D. from the University of Tokyo in 2002. He joined NTT Network Information Systems Laboratories in 1992 and engaged in the development of fast algorithms for cryptographic functions and their software/hardware implementation and the development of a software cryptographic library. From 1996 to 1997 he was a guest researcher at ETH Zurich, where he studied cryptography, especially multiparty computation, supervised by Professor Ueli Maurer. From 1997 to 2004 he was with NTT Information Sharing Platform Laboratories (now NTT Secure Platform Laboratories), where he worked on the design and analysis of cryptographic primitives and protocols, including electronic voting, a key escrow system, blinding signatures for digital cash systems, message recovery, and publicly variable encryption schemes. He also engaged in efficient multi-party computation based on cryptographic assumptions and zero-knowledge proofs in multiparty computation. From 2004 to 2006 he was a visiting researcher at IBM T. J. Watson Research Center, NY, USA, working with the Crypto Group, where he researched hybrid encryption, zero-knowledge proofs, and universally composable protocols. He served as a program chair for the 7th Cryptographers' Track at the RSA Conference on Topics in Cryptology in 2007, ACM Symposium on Information, Computer and Communications Security in 2008, and the 16th Annual International Conference on the Theory and Application of Cryptology and Information Security in 2010. His research interests include digital signatures, public-key encryption, and efficient instantiation of cryptographic protocols.

Keeping the Spatial Relationship of the Eye and Arm Constant Is Important for Motor Learning. Research on Sensorimotor Control Reveals Brain Mechanisms Underlying Movement Control

Naotoshi Abekawa
Distinguished Researcher, NTT Communication Science Laboratories

Overview

The human eye is often mentioned in the sports world in expressions such as "watching the ball." We spoke to Distinguished Researcher Naotoshi Abekawa, who studies sensorimotor control, shedding light on the relationship between eyes and arms with a particular focus on unconscious movement. His goal is to provide new value proposals for the real world, such as sports and user interfaces.

Keywords: sensorimotor control, eye-arm motor coordination, body representation

About NTT's basic research on sensorimotor control

—Please tell us more about your research.

I was originally interested in what makes human beings smart, and my graduation work at university was on image pattern recognition, a field that is part of the growing area of artificial intelligence (AI). After that, I became increasingly interested in understanding human beings themselves, and thus began my current research on sensorimotor control. Sensorimotor control refers to the mechanism whereby the brain processes the information acquired from the sensory organs to generate body movements. Including my master's course, I have been studying this field for over 15 years.

I have placed particular focus on the relationship between eyes and arms, and am now working on three research projects: implicit visuomotor control, mechanisms of eye-hand motor coordination, and the formation of body representations.

—What is "implicit visuomotor control"?

For example, when there is something on a desk, we first look at it with our eyes, recognize what it is, know where we've seen it, make a decision to reach it, and finally move our arms. The process of moving through each of these steps is called "sequential processing."

Such traditional theory is a very good fit for the voluntary motor generation. On the other hand, in cases where there are severe time constraints, such as in sports, the question arises of how movements based on such complex computations can be carried out on time. This is why I focused on implicit and unconscious movement.

For example, if you move the background image in a certain direction during arm motion, the arm will unconsciously follow that direction with a subconscious motor response that occurs regardless of age or gender. Although this motor response cannot be observed without very precise measurements, a series of studies by our group has demonstrated that these subconscious visuomotor control processes exist.

—Tell us about the mechanisms of eye-arm motor coordination.

For example, when you make breakfast or hit a ball flying toward you, your eyes move appropriately to track where your arms will move. This means that the eyes are moving in coordination with the movement of the arm. This project aims to determine whether this co-relationship also applies to subconscious movement, and if so, whether it is identical to voluntary movement or completely separate.

For example, if you think about learning to ride a bike, at first you will have a hard time because you try to pay conscious attention to lots of things, but once you learn how to ride you will stop thinking so much. In our field, we call such improvement of motor skills "motor learning." Our study has shown that the eye plays an important role in unconscious motor learning and the execution of acquired motions, and specifically, that maintaining a constant spatial relationship between the eye and the arm increases the learning effect.

This new concept was also accepted in a presentation at Advances in Motor Learning & Motor Control, 2019, an international conference regarded as the most competitive in the field of motor control and motor learning. This is the project I am focusing most of my efforts on right now.

—Tell us about the formation of body representation.

This project is slightly different from the two I mentioned earlier. Let's take tennis as an example. In order to determine whether to hit back a ball flying toward you with a forehand or backhand swing, you must determine whether the ball is to your right or left. This decision must be made with reference to the body's midline.

However, unlike vision and hearing, there are no organs for perceiving the midline of your body directly. A representation of your body's midline is likely formed based on a range of sensory organs as well as your knowledge and your experience. This project aims to find out how such body representations are formed.

Specifically, through an experiment in which GVS (galvanic vestibular stimulation) electrical stimuli were transmitted to the vestibular organs of the brain, we were able to confirm the movement of egocentric body representations and the deep involvement of

vestibular inputs in the body's midline.

I worked on this project while studying in London in 2015, and it has already produced results, including papers.

In the future, I would like to establish a unified theory of motor control leading to an essential understanding of human beings

—What areas do you expect your research to be applied to in the future?

In the world of professional sports, such as baseball and tennis, there are quite a few players and coaches who refer to the eye with expressions such as "keep your eye on the ball" or "I don't watch the ball much when I am performing at my best." However, this is hard to explain when you consider why.

I thought that the significance of such messages may lie in the idea of keeping the spatial relationship between the eye and the arm constant rather than just looking at a fixed point.

By taking these ideas that are discussed in practical situations and applying them in a research setting, I believe we can uncover the mechanisms of eye-arm coordination, and leverage this knowledge to improve accuracy and efficiency in areas such as sports training and rehabilitation.

Applications could also include user interfaces and virtual reality. For example, if we aim to design a user-friendly, attractive interface for humans, we need to fundamentally understand how humans sense and how they move. Human movement includes both voluntary and subconscious movement. Likewise, the "comfort" that humans feel may be closely linked not only to their voluntary movement, but also to their subconscious movement.

In the medium and long term, this research will also contribute to Digital Twin Computing that IOWN (Innovative Optical and Wireless Network) aims to achieve. It should be clear that the essential understanding of human sensorimotor control that we are aiming for is key to digitally reproducing all aspects of human beings, including not only visual appearance by also inner aspects.

—What do you consider NTT's strengths to be?

I think NTT's strength lies in its close ties to experts in various fields. NTT Communication Science Laboratories, where I work, is a basic research laboratory that is focused on humans and information as its two pillars. Many researchers work there whose methods can be integrated into the field of information as well as machine learning, AI and other areas of sensorimotor generation. The Human Information Science Laboratory, of which I am a member, is also home to numerous experts on topics such as vision, hearing and touch in addition to movement.

Furthermore, within the laboratory, the Kashino Diverse Brain Research Laboratory uses brain science to reveal the outstanding capabilities of the most extraordinary people with a focus on professional sports, and is producing close links between records in our laboratory environment and real-world records.

Starting with the assumption of collaborating from the beginning often doesn't work well, but I think new themes and research are often developed when different values, perspectives and techniques are mixed together. I think this is a major strength of NTT.

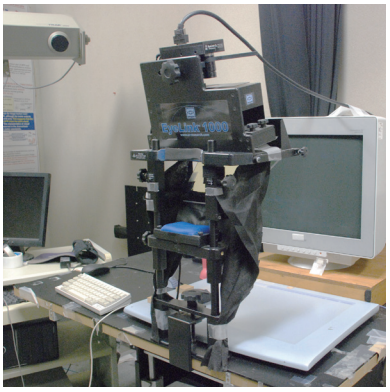
—Do you have a message for people who would like to work in basic research?

I would like to encourage students who aspire to become researchers to just go for it when they are in doubt. Give it a shot first, and then reflect. Depth is obviously important when we think about things, but it is also important to look at data from different directions. Then, once you have put an idea together, take a look at it from a higher perspective. Research is always a continuous struggle, but I think that sticking with this repetitive process builds your own originality and values.

I have recently come to realize that the saying "think like an amateur, do as an expert"* is spot on. Previously, I thought the right approach was to "think like an expert and do as an expert"—in other words, I believed that depth, specialization and almost obsessive focus were key to research success. However, research conducted this way does not have a significant impact. In fact, I have come to realize that the more impactful research results are the product of efforts to use scientific evidence in order to answer questions or understand phenomena that the general public is familiar with—things we encounter in our daily lives, or random occurrences that make us wonder.

In the course of my research, I have come to think that the eye's cooperation with the arm involves more than just acquiring more detailed visual information

* Quote by Japanese robotics engineer Dr. Takeo Kanade.



as thought in the past. As suggested by the common sentiment that "the eyes are windows to the soul," the eye may also be closely related to a person's consciousness, mindset and attention. I would like to explore these ideas further and establish a unified theory of motion that combines voluntary and subconscious movement, leading to a fundamental understanding of human beings.

However, a "fundamental understanding of human beings" is a complex research theme, and there are no departments that align with it in Japanese universities. For this reason, few students possess the relevant expertise; conversely, however, this field is such that people with a variety of specialties and backgrounds can participate.

NTT offers a wide range of paths, including recruitment of newly graduated students with master's degrees and doctoral degrees, as well as mid-career and post-doctoral hires. If you are interested, please visit our website.

■ **Interviewee profile**
Naotoshi Abekawa
Distinguished Researcher, NTT Communication Science Laboratories.
He received a B.E. from Tokyo Metropolitan University, an M.E. from Tokyo Institute of Technology, and a Ph.D. from Kyoto University, in 2003, 2005, and 2013. He joined NTT in 2005 and has been engaged in research on human information processing. His research interests include human sensorimotor mechanisms, especially visuomotor control properties. He is a member of the Society for Neuroscience, the Japan Neuroscience Society, the Japanese Neural Network Society, and the Institute of Electronics, Information and Communication Engineers.

Data-driven Medical and Health Support Created Using Bio-digital Twin

Hiroshi Nakashima, Katsuyoshi Hayashi, and Hideki Gotoh

Abstract

Humanity is currently experiencing a pandemic unprecedented in recent history. In November 2020, NTT announced its Medical and Health Vision, "Realization of the Bio-digital Twin," to create a medical future in which people can avoid unknown risks and remain healthy and hopeful about the future through predictions of their physical and mental states. In the Feature Articles in this issue, NTT's Medical and Health Vision as well as the latest technological details concerning acquiring and analyzing biological information and enabling treatment in the body, namely, elemental technologies concerning bio-digital twins, are introduced.

Keywords: Medical and Health Vision, bio-digital twin, well-being

1. New expectations in the medical and healthcare fields

Humanity is in the midst of the Covid-19 pandemic, which has severely affected daily life, healthcare, and social systems. Covid-19 has large regional and individual differences in its symptoms, severity, case-fatality rate, and prognosis, and it has reminded us of the vast extent of the unknown areas in the living body. Even now, ensuring the safety of citizens and medical personnel and protecting the lives of citizens are urgent issues.

At NTT, we believe that for people to overcome unknown risks, live a safe and secure life, and lead a happy life in their own ways, it is important for them to be able to maintain hope for the future as well as their physical and mental health. To achieve these goals, we believe that there is a greater need than ever for (i) early detection of abnormalities in the body caused by unknown risks, (ii) prevention and treatment based on the causal relationship between the onset and worsening of diseases, and (iii) individualization and optimization of support for people who require nursing care and people with disabilities.

2. Our Medical and Health Vision: Realization of Bio-digital Twin

In response to the needs described above, NTT is aiming to create a precise mapping of each person's body and mind, a so-called "bio-digital twin" (BDT) (**Fig. 1**), by applying Digital Twin Computing, which is one of the components of NTT's Innovative Optical and Wireless Network (IOWN). Our vision is to contribute to the future of medical care, in which people are healthy and have hope for the future, by predicting their physical and mental conditions through BDTs (**Fig. 2**). We believe that BDTs can form not only individual mappings but also aggregate mappings of an unspecified number of individuals. In addition to the medical care provided by medical professionals, the medical care described here includes healthcare, long-term care, and support for people with disabilities.

To predict the future for the mind and body, five goals must be reached. The first is digital mapping of

Fig. 1. Schematic of bio-digital twin (BDT).

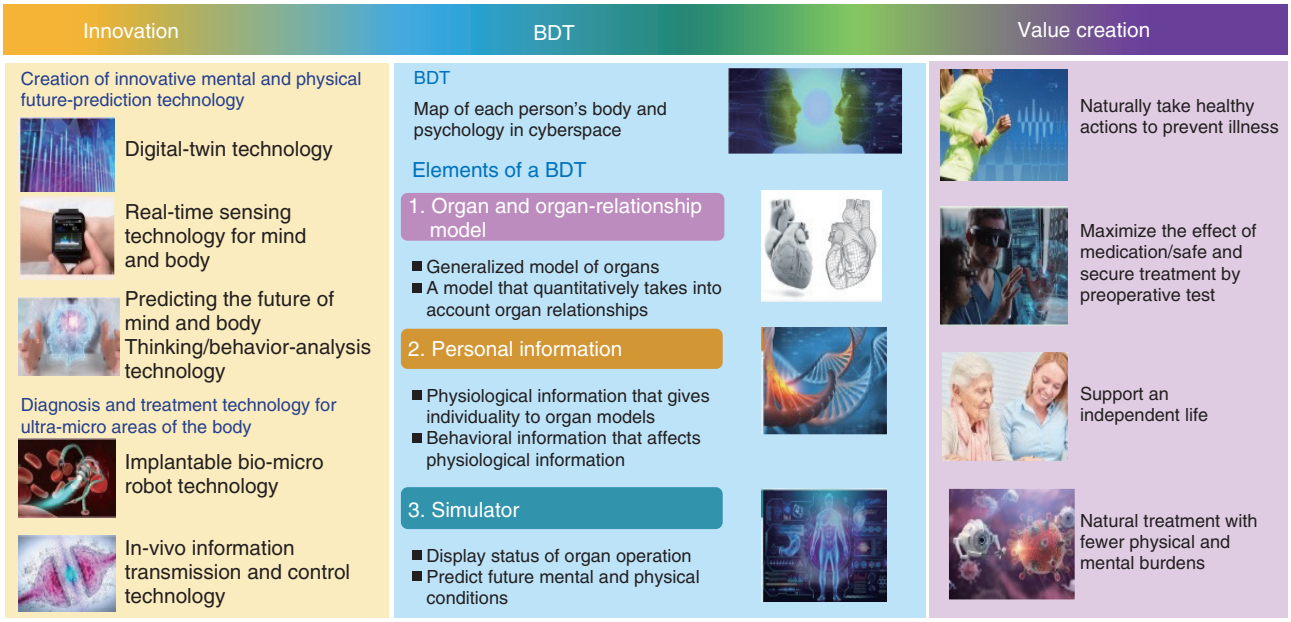


Fig. 2. NTT's Medical and Health Vision.

organ functions. Focusing on heart disease, with which the number of patients is expected to increase rapidly and which significantly decreases quality of life when it develops, we have begun studying cardiac modeling. The living body changes with each passing moment according to the environment it is in and the load on it. The second goal is therefore to measure biomarkers, such as electrocardiograms, heartbeat, and blood glucose level, constantly or in a timely manner while imposing little or no burden on the

body and mind. The third goal is predictive simulation of psychosomatic states from a multifaceted perspective, including human behavioral mechanisms, psychology, and diseases involving multiple organs. In addition, we believe that it is necessary not only to predict the future but also to link those predictions to specific treatment and support. In particular, we are also focusing on the fourth and fifth goals: diagnosis and treatment in the ultramicroscopic region of the body and control of limb movements in accordance with signals from the central nervous system. Reaching these goals will lead to nursing care and support for people with disabilities.

To reach each of these five goals, we are researching and developing technologies such as technology for creating each person's digital twin, non-invasive real-time sensing for the mind and body that captures the individuality of each person, future prediction for mental and physical conditions, thinking-and-behavior analysis, implantable-device and bio-micro-robot technology using highly biocompatible materials, and information-transmission and control implemented within the living body. In heart modeling, for example, we are simulating the function of the cardiovascular system that instantly controls the autonomic nerves and blood volume. The simulation is based on a hemodynamic model into which data, such as right-atrial pressure of the heart and pulmonary-artery pressure are input and central venous pressure and cardiac-excretion amount, are output. Using this knowledge, we are focusing on mechanisms that work in multiple layers to maintain homeostasis in the whole body by, for example, regulating load over long time scales due to lifestyle and daily stress.

A BDT is constructed from personal information with the consent of the individual on which it is based. That personal information includes sensing data collected in real time, as described above, molecular biological information of organ functions (such as genomes and proteins), and information about exercise, diet, and behavioral history that affect physiological states. While carefully considering privacy and ethical issues, we will use the assets of NTT Group companies to collect and use personal data. A BDT, which is based on a variety of information, can be used to assess a person's mental and physical state from the past to the future while taking into account the influence of the person's thoughts and surrounding environment. We believe that it is possible to use a BDT to predict and avoid unknown risks that are difficult to deal with on an individual basis. We expect a BDT to enable improvements such as (i) maximizing the effect of medication and therapeutic effects by pre-simulation of surgery and (ii) improving natural lifestyle habits unconsciously derived from individual behavioral mechanisms without forcibly suppressing diet (which might adversely affect a person's health). We also aim to use BDTs in use cases such as supporting the independent life of elderly persons.

3. NTT R&D in the medical and healthcare fields

In the medical and healthcare fields, as information and communication technology (ICT) and artificial intelligence (AI) analysis continue to be introduced, we are trying to make major innovations while incorporating the latest diagnostic and therapeutic technologies for remote, non-contact, daily, and home use. With the advent of the Internet of Things era, wearable healthcare devices, which allow users to easily monitor their body condition on a daily basis, are becoming increasingly competitive worldwide as various measurement functions are added to the devices. Against this background, NTT established the Biomedical Informatics Center (BMC) in July 2019 as a domestic research center in the medical and healthcare fields. Making it our mission to create data-driven medical and healthcare using ICT and AI technologies, we are promoting research and development (R&D) in cross-sectional collaboration with related NTT laboratories for making our Medical and Health Vision a reality.

NTT laboratories are engaged in a wide range of research—from basic to applied—while focusing on themes representing the building blocks of a BDT, such as future prediction technology for the body and mind, bio-sensing technology (wearable, remote, and non-invasive), cardiac-abnormality detection and prediction technology, and micro-therapy technology inside the body. Together with the Medical & Health Informatics Laboratory (MEI Labs) of NTT Research, Inc., which is an overseas research base established in July 2019, we are accelerating R&D from a global perspective and promoting co-innovation with global partners. We will also work closely with NTT Group companies to expand the area of commercial services in the medical and healthcare fields. In these rapidly evolving fields, to achieve results quickly and implement them in society in accordance with our Medical and Health Vision, it is difficult for the NTT Group alone to establish medical technologies and understand

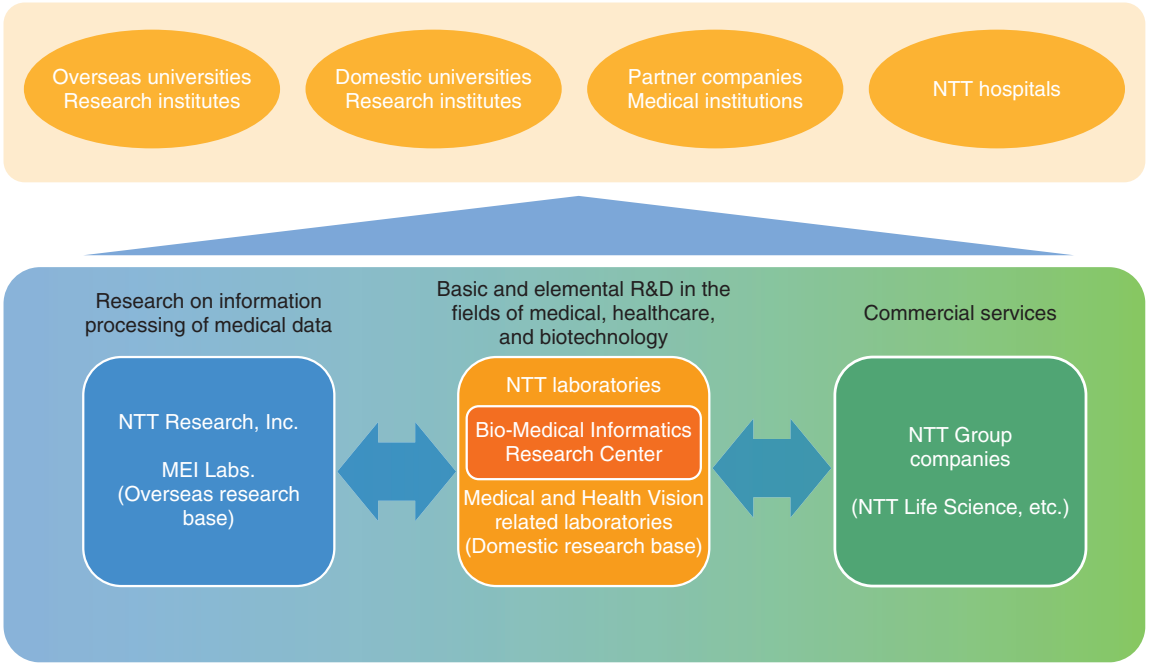


Fig. 3. Formations supporting medical science and business.

social, clinical, and advanced needs. With that difficulty in mind, we want to promote R&D through collaboration and co-creation with medical institutions, research organizations, universities, partner companies, and NTT Group hospitals in Japan and overseas. Readers should refer to the five articles in this issue (described below) for specific details about our R&D for making our Medical and Health Vision a reality (**Fig. 3**).

In the first article, titled "Efforts in Analyzing Risks and Factors Concerning Lifestyle-related Diseases and Long-term Care" [1], prediction and factor analysis of the risk of disease onset based on machine learning and AI—which aim to provide health guidance tailored to individual characteristics and lifestyles—are introduced. The main topics outlined in this article are factor analysis of disease onset considering genomic information and prediction of locomotive syndrome to prevent the need for nursing care.

The second article, titled "Behavior-change Support Technology that Brings About Positive Mental Changes" [2], focuses on the issue of health promotion, through lifestyle improvement and other measures, to address social issues such as reducing medical costs. This article introduces R&D themes for improving lifestyle habits (so-called "behavioral change") by providing advice tailored to each person's personality.

In the third article, titled "Technology for Visualizing the Circadian Rhythm: Wearable Core-body-temperature Sensor" [3], biological sensing of core body temperature, which can be used as an indicator of common colds and infectious diseases, insomnia, depression, and other body rhythms, is introduced. Continuous daily monitoring of deep body temperature—which had been difficult to easily measure—by using wearable device technology that does not place a burden on the body is also discussed.

In the fourth article, titled "New Technology for Measurement and Analysis of Biological Sounds and Electrocardiographic Signals—Toward Early Detection of Heart Disease and Rehabilitation by Using Personal Heart Modeling" [4], a method for measuring bio-acoustics by using a wearable acoustic-sensor array and new bio-signal measurement and analysis techniques (such as tensor electrocardiograms obtained by hitoe™) are introduced. Personal cardiac modeling, cardiac-abnormality detection and prediction technologies, and their applications to rehabilitation are also described as core technologies of BDTs of the future.

The fifth article, titled "Bionics Technology for the Future of Medicine and Health" [5], focuses on bionics technology, which bridges the fields of biological

systems and engineering, with a view to future micro-therapeutic technologies deployed in the body. Two technologies are introduced: (i) soft-material device technology for implementing microphysiological systems, which imitate the shape and movement of living organisms by applying the knowledge of biological systems to engineering systems, and (ii) bio-cybernetics technology, which applies engineering knowledge to biological systems, processes biological signals, and returns them to the living body to activate movements of the body. Microphysiological systems are expected to be able to reproduce and evaluate organ models and multi-organ connection models from the cell and biomaterial levels. In contrast, bio-cybernetics is highly valued in terms of providing technology for rehabilitation and handicap support. We believe that both are challenging research themes.

As described above, we have begun to work on themes of R&D in various technical fields toward making our Medical and Health Vision, "Realization of BDTs," a reality. In close collaboration with personnel of NTT Group and external partners as we pursue co-creation, we will continue to contribute to the improvement of the well-being of people and society as a whole from the aspect of R&D.

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He received a B.E., M.E., and Ph.D. in applied chemistry from Waseda University, Tokyo, in 1995, 1997, and 2002. He joined NTT Basic Research Laboratories in 1997. Since then, he has been engaged in research on the synthesis and control of the optoelectrical properties of (semi)conductive polymers and nano-bio materials. His recent work includes research on biomonitoring using the functional material hitoe™ wearable bioelectrodes. He was a visiting researcher at University of Oxford, UK in 2002 and at University of Wollongong, Australia in 2010–2011. He is a member of the Chemical Society of Japan (and its Division of Colloid and Surface Chemistry) and the Japan Society of Applied Physics (and its Division of Molecular Electronics and Bioelectronics).

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He received a B.E., M.E., and Ph.D. in applied chemistry from Waseda University, Tokyo, in 1996, 1998, and 2005. He joined NTT Basic Research Laboratories in 1998 and began researching electrochemical biosensing devices to detect biomolecules, including neurotransmitters and hormones in the brain and blood. From 2007 to 2008, he was a visiting scientist in the Biomedical Engineering Department, University of Wisconsin-Madison, Wisconsin, USA, where he studied cell biology with microfluidic devices. In 2017, he began working with various stakeholders to create new value using NTT R&D products. He is also working as a senior research engineer at NTT Device Technology Laboratories and Bio-medical Informatics Research Center, NTT Basic Research Laboratories.

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Efforts in Analyzing Risks and Factors Concerning Lifestyle-related Diseases and Long-term Care

Akihiro Chiba, Naoki Asanoma, Shozo Azuma, Akinori Fujino, and Syunsuke Aoki

Abstract

For a person to continue a healthy life, it is important for him/her to become aware of the risk of illness as soon as possible and take appropriate countermeasures. To help people live a healthy life, NTT is researching and developing technology for predicting disease risk by using machine learning and analyzing the risk factors from data on health-diagnosis results, genomic information, and data obtained from large-scale cohort surveys. Analysis of genomic data targeting lifestyle-related diseases and analysis of cohort-survey data targeting locomotive syndrome (which is attracting attention as a factor requiring long-term care) are introduced in this article.

Keywords: machine learning, genome data analysis, locomotive syndrome

1. Toward a healthy life that suits each person

We believe that most people have a desire to avoid illness and live a healthy life in old age. However, 19.7% of men and 10.8% of women are suspected of having type 2 diabetes, which is a lifestyle-related disease [1]. Moreover, the percentage of people aged 75 and over who have been certified as requiring long-term care is 23.3%, and that number is increasing yearly [2].

To prevent lifestyle-related diseases and the need for long-term care, it is necessary to recognize health risks as early as possible and consider what countermeasures to implement. NTT aims to contribute to both these steps by using information and communication technology (ICT). To make people aware of health risks, we have been working on (i) predicting the risk of severe disease in diabetic patients by using medical information [3] and (ii) predicting the risk of developing lifestyle-related diseases by using the results of health checkups [4]. We are currently researching and developing technologies for helping people become aware of health risks and take countermeasures.

To develop countermeasures, it is necessary to understand the relationship between the disease and risk factors such as a person's unique characteristics, past medical history, and current lifestyle. In this article, our efforts to analyze the relationship between a person's unique genomic data and lifestyle-related diseases as well as the relationship between cohort-survey*1 data (including lifestyle habits) and locomotive syndrome for preventing the need for long-term care are introduced.

2. Factor analysis according to individual characteristics

We first introduce our efforts regarding analysis of genome data. NTT and the Institute of Medical Science of the University of Tokyo established the "Project Division of Genomic Medicine and Disease

*1 Cohort survey: A survey to track the incidence of disease in a certain population by conducting periodic health examinations, etc.

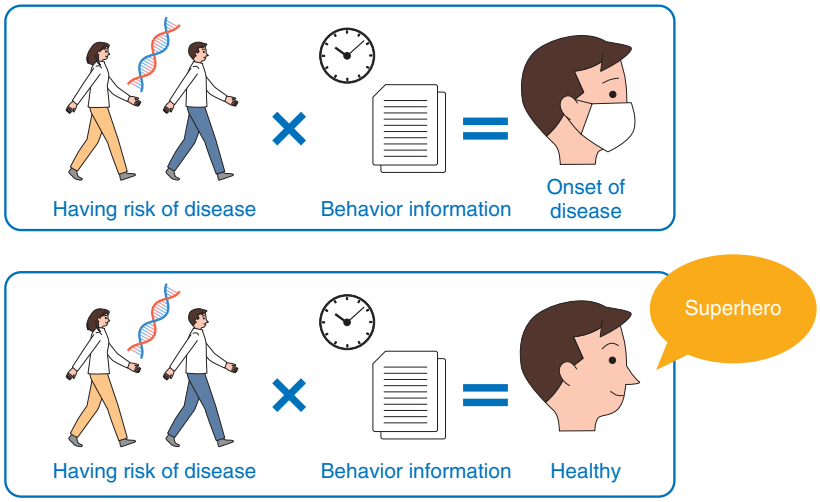


Fig. 1. "Superhero" model.

Prevention" in July 2019, which is a joint research project to elucidate disease-risk factors on the basis of genomic information and visualize desirable behaviors and lifestyles that prevent disease [5]. We are developing a database for collecting and analyzing (i) genomic information obtained from genetic tests as well as (ii) health-checkup results and time-series data about lifestyle habits of company employees who consented to participate in the research [6]. As a result of these developments, it will be possible to conduct research from two aspects; innate factors, such as individuals' genomes, and acquired factors, such as the environment in which people live, that affect their health status. Within the framework of this collaborative research, NTT decided to analyze the characteristics of "superheroes" in regard to maintaining health.

Superheroes in this context are people who, according to their genetic information, have a high risk of lifestyle-related diseases but maintain their health without developing them. This is the model proposed by NTT Life Science, which is a provider of genetic-testing services (**Fig. 1**). To find superheroes from the data, groups that are genetically at high risk or low risk of developing a disease are first divided on the basis of one or more single nucleotide polymorphisms (SNPs), i.e., differences in one base in the DNA base sequences of individuals that are related to the disease and already known from previous research. Other groups are divided on the basis of onset or non-onset of the disease. The general flow of data analysis is to analyze—by using a statistical method—whether there are any differences in data characteristics between combinations of these groups. If the physical condition and behavioral characteristics peculiar to superheroes obtained from the analysis of data on the basis of genetic-test results and health-checkup results are applied, it will be possible to identify factors for maintaining health and provide advice for improving health and link those factors to effective behavior change and disease-risk aversion.

By applying the risk-prediction technology for lifestyle-related diseases developed by NTT [4], it will be possible to predict the risk of disease onset and analyze factors according to the individual characteristics of a person by using genetic information and time-series data of health-checkup results. Lifestyle-related-disease risk-prediction technology makes it possible to predict the risk (probability of onset) until the onset of a disease by learning to rank that takes into account censored data. By combining the information from the risk-prediction model with the information on genetic disease risk, we believe that we can conduct a more detailed analysis of factors that contribute to health maintenance.

3. Factor analysis considering lifestyle, etc.

We now introduce our efforts in preventing the need for long-term care. Preventing such a need is an important social issue in Japan's "super-aged society" because it not only reduces social-healthcare costs but also improves the quality of life of the caregivers and the cared-for. To prevent long-term

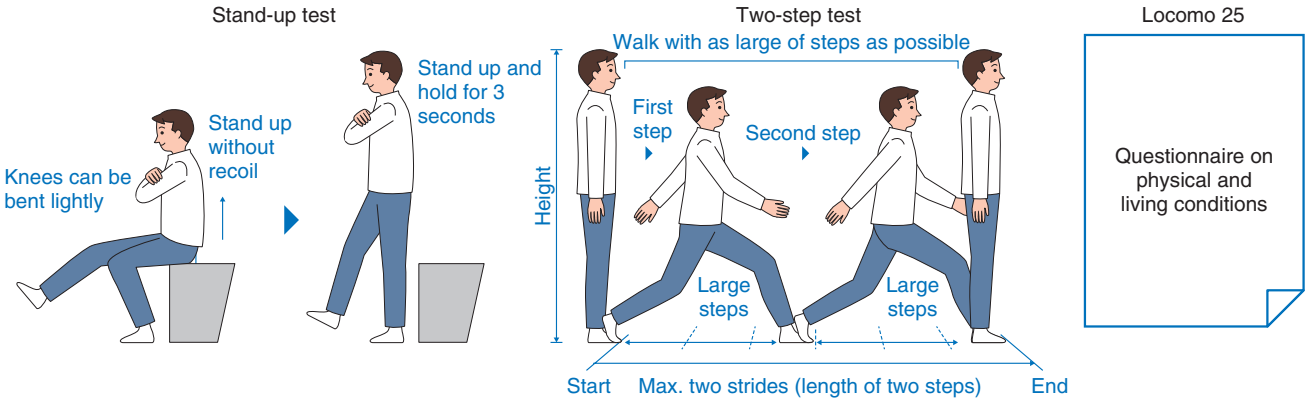


Fig. 2. Locomotive syndrome risk test.

care, we are working to elucidate the factors leading to long-term care and quantify risk by using the analysis technology and knowledge of medical and health data that we have accumulated thus far. To prevent the need for long-term care by using data analysis, data and medical knowledge concerning many elderly people are required. In April 2020, NTT established the Department of Preventive Medicine for Locomotive Organ Disorders at the 22nd Century Medical and Research Center of the University of Tokyo Hospital and began joint research.

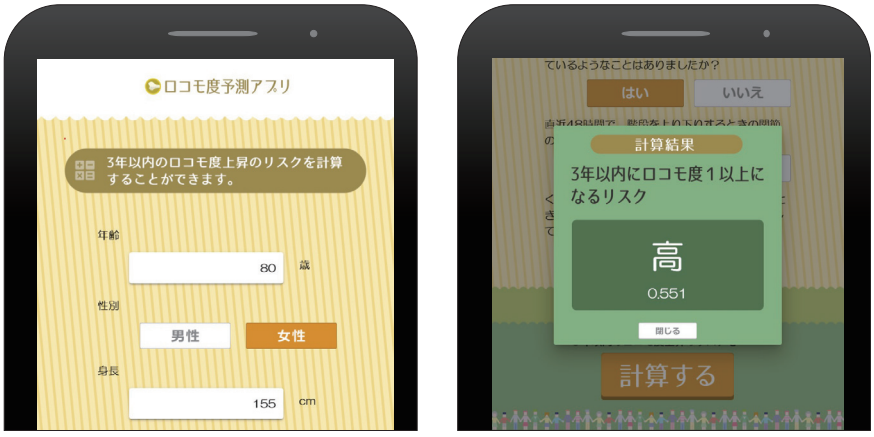
In this joint research, we are investigating the causes of diseases related to the need for long-term care and intervention methods from data of about 4400 people collected from a cohort survey conducted over 15 years. According to a survey conducted by the Ministry of Health, Labour and Welfare, dementia is the most common cause of the need for support or care [1]. However, the proportion of fractures, falls, and joint diseases, which are related to the decline of motor and mobility functions, exceeds that of dementia, and the combination of both has become the largest proportion. In this joint research, we are focusing first on the decline in motor and mobility functions.

Locomotive syndrome is a concept that describes the decline in motor and mobility functions. Defined as "Locomotive syndrome means being restricted in one's ability to walk or lead a normal life owing to a dysfunction in one or more of the parts of the musculoskeletal system – muscles, bones, joints, cartilage, or the intervertebral discs" [7], it is an important concept regarding preventing the need for long-term care. Locomotive syndrome is classified using an index called the locomotive syndrome risk level from 1, least severe, to 3, most sever [7]. It is determined from the results of a stand-up test, a two-step test, and the "Locomo 25"[*2] test (**Fig. 2**). For example, if one cannot stand up with one leg after sitting on a chair with a height of 40 cm, your locomotive syndrome risk level is deemed as 1. This result means their mobility function has begun to decline.

Although locomotive syndrome is an important concept regarding preventing the need for long-term care, awareness of it is currently around 43.8% [8]. In particular, younger generations are active and less likely to feel the risk of locomotive syndrome. However, we believe that identifying the risk of decline in mobility function from a young age and making early behavioral changes can reduce the risk of locomotive syndrome and ultimately reduce the risk of requiring long-term care. Therefore, to make it easier for many people to understand the risk of locomotive syndrome, we constructed a model for predicting future locomotive syndrome risk level by analyzing a large amount of data obtained from a cohort survey and implemented it in a research application (**Fig. 3**). By answering about 20 questions about age, weight, lifestyle-related topics via the app, users can predict their risk of having the locomotive syndrome risk level of 1 or higher in the next three years.

In a typical cohort survey, more than 1000 analytic elements are collected from health checkups and questionnaires completed by participants. In general, prediction accuracy will be higher if many factors are used in the analysis. Regarding our study, prediction accuracy will be higher if all the elements of the cohort survey are used. However, from the standpoint

*2 Locomo 25: A test in the form of 25 questions in regard to locomotive syndrome.



Input age, height, weight, etc. and answer lifestyle-related questions

Risk of having the locomotive syndrome risk level of 1 or higher in the next three years: High

Fig. 3. Screen of app for predicting the locomotive syndrome risk level.

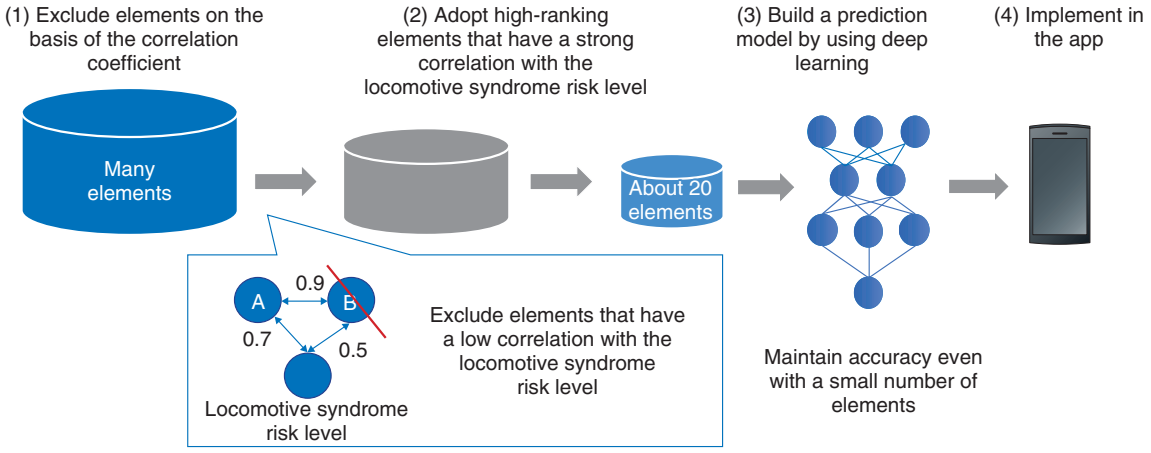


Fig. 4. Procedure from data analysis to application.

of the users of the application, we thought it would be better to obtain risk-prediction results by having them answer as few questions as possible. We therefore focused on the usability of the application and built a model that can predict the risk of locomotive syndrome with fewer elements while maintaining prediction accuracy (**Fig. 4**).

The necessary elements were optimized in accordance with the correlation among them. For example, when elements that were strongly correlated, such as diastolic blood pressure and systolic blood pressure, the element with the lower correlation with the locomotive syndrome risk level, which is the prediction target, was deleted. Therefore, the need for users to answer similar questions was eliminated, and the ability to efficiently enter the information required for prediction was improved. Next, about 20 elements that had a large correlation coefficient with the locomotive syndrome risk level were extracted as the elements that were input into the application. Using the correlation coefficient makes it possible to understand which behavior among the extracted elements contributes to the increase in the locomotive syndrome risk level and to take measures to prevent locomotive syndrome. Finally, a multi-layer neural network that predicts the locomotive syndrome risk

level by using deep learning was trained, and a prediction model based on that network was built. It thus became possible to predict the locomotive syndrome risk level with a certain degree of accuracy even in the case of a small number of elements. Since the trained prediction model can be incorporated into the app and easily executed on a personal computer or smartphone, risk can be predicted even during a health checkup, for example.

The elements that were narrowed down included those related to exercise habits as well as questions related to pain. We were able to find elements that were not considered medically important thus far and confirm the value of analysis from this cohort survey data. In the future, we will verify the effectiveness of implementing health education via the app to prevent the need for long-term care.

4. Future of health support using ICT

In this article, taking lifestyle-related diseases and prevention of long-term care as examples, risk prediction and its factor analysis were introduced. We believe that predicting the future through machine learning and artificial intelligence will trigger a review of people's current behavior. We also believe that analyzing the factors that can change the future will help people change their behavior. We expect that from now onwards, various medical and health-related information—such as electronic medical-record data, healthcare data such as blood pressure measured daily, and biological information measured using wearable devices—will be collected. Each piece of data can only represent a part of a person's overall health status; however, by connecting those data, it becomes possible to understand the person from multiple perspectives. As a result, we believe that by fusing and analyzing large-scale data and medical knowledge, we can simulate complex events occurring in the body and reproduce them in digital space. In the future, we want to (i) contribute to developing the bio-digital twin, which will make it possible to simulate an entire person, by developing technologies related to risk prediction and (ii) make it possible to predict unknown events in the body and understand complex events.

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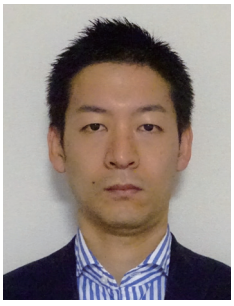

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Behavior-change Support Technology that Brings About Positive Mental Changes

Naoto Abe, Tae Sato, and Reiko Aruga

Abstract

Social issues, such as reducing medical expenses and promoting people's health by improving their lifestyle habits, need to be addressed. This article uses lifestyle improvement as a use case to introduce a technology to support behavioral change by providing advice tailored to the individual's personality.

Keywords: mental change, behavior change, health promotion

1. Introduction

To address social issues, such as reducing medical costs, three requirements must be satisfied: promoting health by improving people's lifestyles, improving social environments, and encouraging preventive medicine. It is said that multi-stage life planning will be necessary when we enter an era referred to as the longevity society in which people will have lifespans of 100 years [1]. Diversity is required regarding work and relationships, but at the same time, how healthy people can live over that long lifetime is important. Considering these circumstances, we believe that it is important to support behavior change tailored to each person's personality that brings about positive mental changes. Accordingly, we are aiming to implement technology that supports such behavior change in a manner that deeply understands each person's hopes and what they cherish. We believe that such behavior-change support technology will be introduced into health-advice-presentation systems that can be used on a daily basis and into support systems for social-support[*1] services. In this article, our efforts thus far and our newly launched narrative-type behavior-change support technology is introduced.

2. Research on behavior change concerning notification content, timing, and expression

We first introduce our research on behavior change for improving people's lives by presenting health advice, which has been one of our initiatives. There are services that provide advice on how to take action to improve one's health via notifications on smartphones and smartwatches. For example, one service detects when a person is under severe stress and encourages them to take a deep breath [2], and another service encourages a person to stand up and move their body when they have been sitting down too long [3]. However, if the person who receives the message is not motivated to take the recommended action for various reasons, such as the timing is not right or the content is not specific enough, the likelihood that the person will take action (such as exercise) decreases. To encourage a person to take action after receiving a message, it is therefore necessary to tailor the content, timing, and expression of the notification to that person.

With the above background in mind, we conducted an experiment on presenting specific advice on diet, exercise, and breaks to office workers. Specifically,

*1 Social support: Support provided on the basis of relationships between people in social connections. It includes emotional support, informational support, instrumental support, and evaluation support.

Table 1. Advice and implementation rate.

Advice text	Implementation rate (%)
When taking a break (for the restroom, lunch, etc.), walk quickly to your destination	94
When taking a break (for the restroom, etc.), walk faster than usual	87
During desk work, focus on your abdominal muscles and be conscious of correcting your posture	71
When taking a break (for the restroom, etc.), take longer strides more than usual	68
Throw away the trash from your desk yourself	67
Raise your heel five times during short breaks such as waiting for the elevator	61
Climb more than three flights of stairs	61
When taking a break (for the restroom, etc.), walk there while raising your thighs intentionally	57
Climb up more than one flight of stairs	54
Squat five times during short breaks	50
Walk down more than two flights of stairs	37
Raise your heels 20 times while commuting on the train, etc.	36
During lunch break, climb up two flights of stairs	35
Perform two sets of heel raises 20 times during short breaks such as waiting for the elevator	30
Take a 10-minute walk during your lunch break	20
Do two sets of five squats that are a heavy load for you during your breaks	20

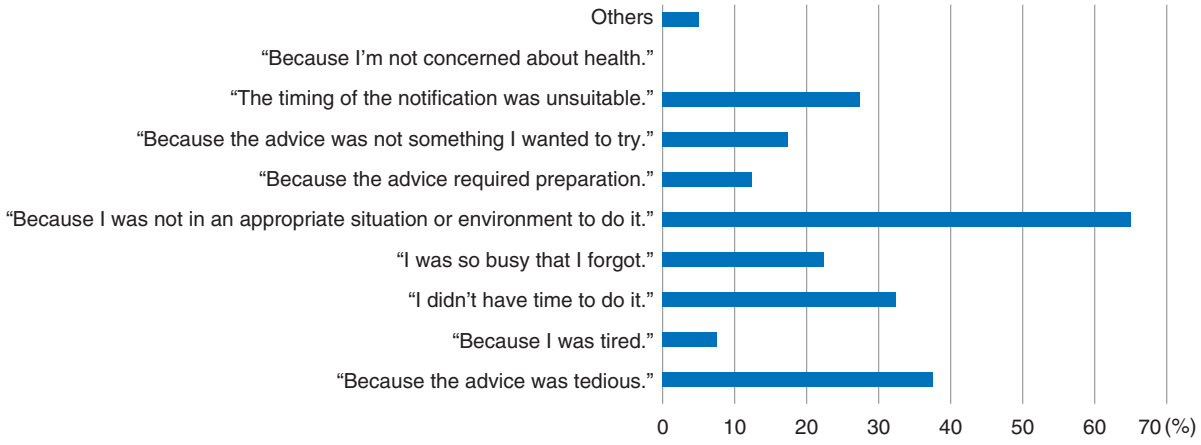

Fig. 1. Main reasons the advice could not be taken.

the participants were sent various messages from a smartwatch app, and whether they actually carried out the advice in the messages was recorded during the experiment. The implementation rate for each message was calculated after the experiment (**Table 1**). The results listed in Table 1 show that the implementation rate is high if the advice is easy to follow. However, the most common reason for not being able to take the advice was that the situation or environment was not suitable to do so; for example, the advice was sent during a meeting (**Fig. 1**). We concluded that if the user’s life pattern is understood in advance and the presentation of the advice is tailored to the context, it will bring about a psychological change in the person who has the time to try it, and that change will lead to behavioral change.

We also studied how the message is expressed. We asked the question, “What kind of expression would bring about a mental change to try the same behavioral advice?” and came up with the following four criteria as patterns of motivation to engage in healthy behavior upon receiving the advice message. Focusing on the psychological phenomenon of cognitive dissonance [4] and time preference for future health

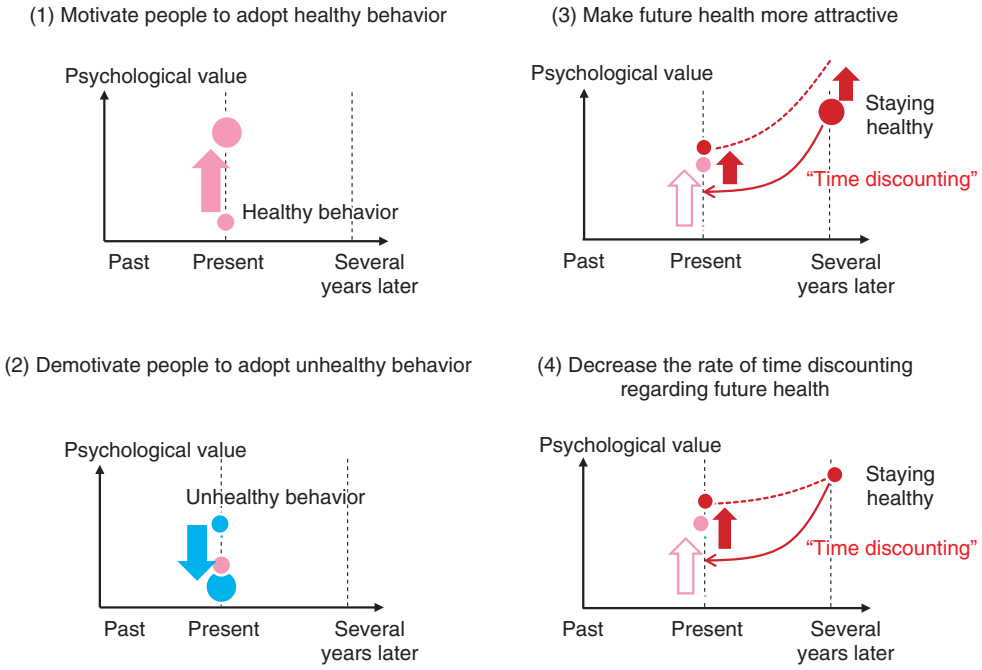

Fig. 2. Four criteria to increase psychological value regarding healthy behavior.

[5, 6] proposed by Festinger, we devised an intervention message pattern to increase the psychological value of healthy behavior (**Fig. 2**). We prepared four messages that changed in accordance with the criteria.

The targets were people in their 30s to 60s who had received no previous guidance for the treatment of lifestyle-related diseases, were willing to lose weight, and were not in the stage [7] of maintaining behavior change regarding exercise and diet. We screened 162 people so that the population would be roughly equal in terms of personality traits ("Big Five"[*2]) and thinking traits (time preference). In a questionnaire, the participants were asked to imagine the situation in which they have about half a day at home doing nothing in particular but watch television and were in good physical condition and could exercise for about 30 minutes (including preparation time). They were then asked to answer the following question: "When you were notified (of the intervention message), did you try to do the exercise that you answered you said is easy to do?" We obtained responses using a six-point scale of 1 (not at all) to 6 (very much). When we looked at the messages with the highest scores, we found that messages related to improving future health had the highest scores (**Table 2**). We thus believe that by changing the content, timing, and expression of messages about recommended behaviors, the degree of influence on the recipients will change, and that change may lead to behavioral changes.

3. Behavior-change support focusing on narrative (narrative-type behavior-change-support technology)

The efforts introduced above can be called "behavior-change support," that is, changing someone's behavior by encouraging them (nudging them) to elicit feelings such as "I think I can do it" and "Let's try it" when the user seems ready to act. To establish behavior-change support, having a deeper understanding of each person's hopes and what they cherish is important. We therefore focused on a person's "narrative" regarding medical care and welfare, where the narrative is a story of an event from the perspective of that person. The narrative contains the person's interpretation of an event to try to determine what the person values and dislikes from the narrative. Nonverbal information, such as facial expressions

*2 Personality traits ("Big Five"): Five elements that represent a person's personality in the "Big Five" theory, which are openness to experience, conscientiousness, extroversion, agreeableness, and neuroticism.

Table 2. Messages with high scores from participants.

Motivational message	Average value	Criteria
Imagine 10 years from now. If you develop a lifestyle-related disease, it will prevent you from what you are enjoying in your life now (e.g., traveling, drinking alcohol, eating ramen, and playing sports). For example, some people have diabetes and struggle with daily blood-glucose measurements and insulin injections, and others have renal failure due to diabetic nephropathy and receive 15 hours of dialysis treatment each week. Today, why not try "30 minutes of exercise that you said is easy to do."	4.60	(3)
Imagine 10 years from now. Being healthy will allow you to continue what you are enjoying (e.g., traveling, drinking alcohol, eating ramen, and playing sports). So why not try "30 minutes of exercise that you said is easy to do."	4.50	(3)
If you do "30 minutes of exercise that you say is easy to do," you can burn about four times more calories than watching TV.	4.49	(1)
If you bend your arms slightly and pull your elbows slightly backwards during the "exercise that you said is easy to do," you can use the pectoralis major muscles and prevent stiff shoulders.	4.49	(1)
A person who developed diabetes at the age of 38 and started dialysis treatment at the age of 50 after neglecting metabolic syndrome said, "If you don't diet and exercise properly, you'll end up like me. So before ending up like me, listen to what I have to say: It's not too late!" Today, how about doing the "30 minutes of exercise that you said is easy to do."	4.48	(3)
A person said, "I used to hate looking at my stomach every time I took a bath, but after two weeks of exercising three times a week, I've lost weight, my body is toned, and I'm proud of my body." So, today, why don't you try to do the "30 minutes of exercise that you said was easy to do."	4.41	(3)
If you do the "30 minutes of the exercise that you said were easy to do" and consume 100 kcal every day, you will lose 1 kg of fat (= 7200 kcal) in 72 days.	4.40	(3)
The "exercise that you say is easy to do" uses large muscles such as the thighs, so it increases energy metabolism."	4.40	(3)

and gestures that the person makes when speaking, can also reflect the strength of the person's emotions and values. Considering the facts described above, we want to draw out a narrative from each person, comprehensively understand the verbal and nonverbal information about the drawn-out narrative, understand the person's personality from this information, and use it to support behavioral change. We call the behavior-change support brought about by such an approach "narrative-type behavior-change-support technology."

4. Toward implementation of narrative-type behavior-change-support technology

Currently, we are trying to understand patients' narratives by conducting interviews with public-health nurses and patients regarding health consultation to extract their personalities that can be used for supporting behavior change. From interviews with public-health nurses who are skilled at eliciting behavioral changes of patients, we are proceeding with the hypothesis and its verification in regard to (i) how public-health nurses draw out patients' stories during consultations; (ii) from what viewpoint do they try to understand the patient with respect to the medical-examination and medical-questionnaire data as well as the content and facial expressions of the response (i.e., narrative) from the patient during consultations; and (iii) what kind of advice should be presented in accordance with the characteristics elicited from the patient.

We will refine our points of focus together with public-health nurses and present health advice that captures the personality of the person (including online). We also plan to verify whether that advice can cause behavior change and be applied to social support.

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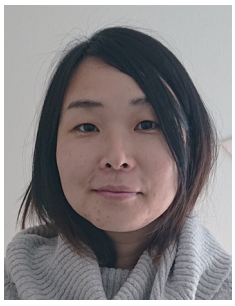

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Technology for Visualizing the Circadian Rhythm: Wearable Core-body-temperature Sensor

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Abstract

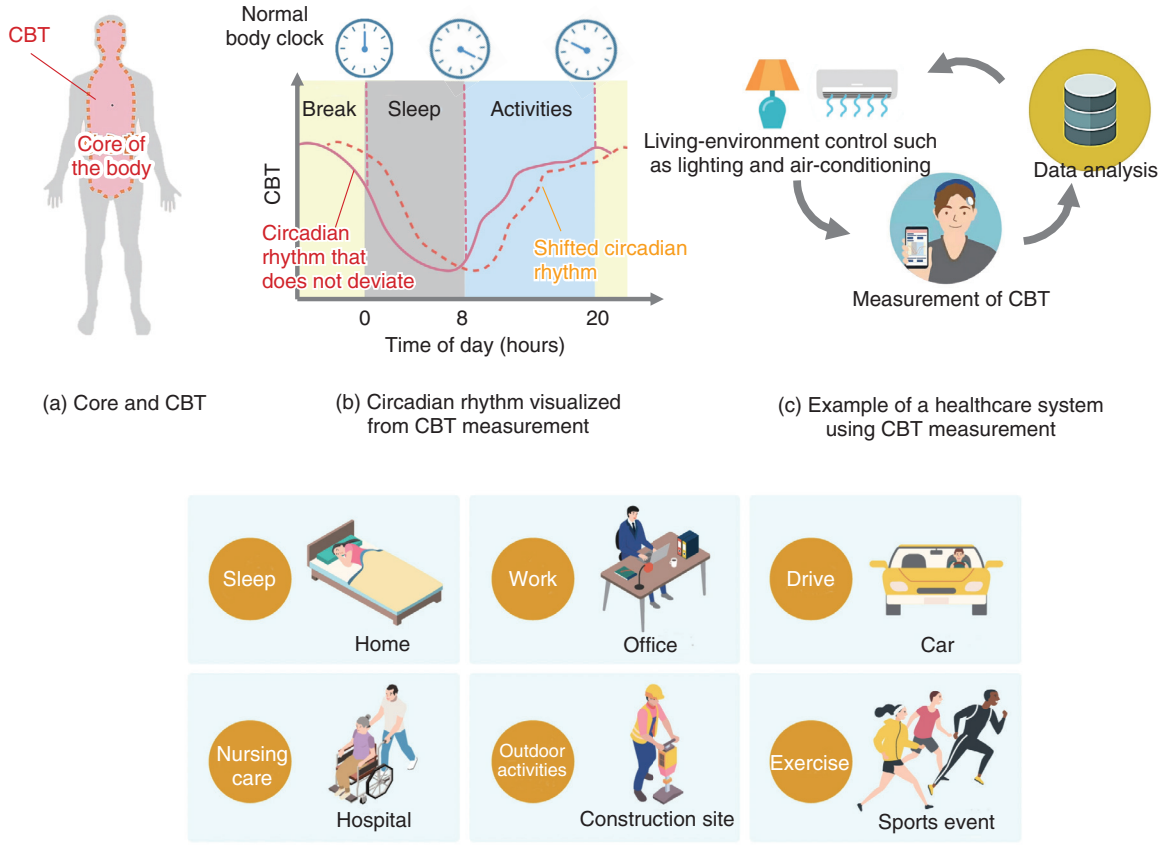
Core body temperature (CBT) is an important vital sign and has been attracting attention as an index reflecting the circadian rhythm of the human body. Since CBT is the temperature at the core of the body, it is necessary to insert a sensor into a body cavity to accurately measure it, which puts a heavy burden on the individual having his/her temperature taken. At NTT, focusing on the flow of heat in the body, we are researching technology that makes it possible to measure CBT simply by affixing a sensor to the body. In this article, the current progress of this research is introduced.

Keywords: circadian rhythm, core body temperature, non-invasive

1. Advanced health management enabled by measurement of core body temperature

As shown in **Fig. 1(a)**, core body temperature (CBT) refers to the temperature of the core of the body, which includes the brain and organs. To protect the functions of those organs, CBT is not easily affected by the outside environment and is maintained at the highest temperature in the whole body. CBT increases as a result of inflammatory reactions, such as heat stroke and infectious diseases, and decreases with the onset of hypothermia and hypothermia treatment; therefore, it is used as an important vital sign. CBT fluctuates by about 1°C in a daily cycle even within the normal temperature range. This fluctuation is linked to the circadian rhythm of the body [1]. Recent studies have shown that circadian rhythms are closely related to our physical condition in terms of sleep, exercise quality, onset of illness, and so on. In today's society, in which people have diversified lifestyles, it is easy for the circadian rhythm to become out of sync with the time of day. A common example is a person's bedtime and time of getting up becoming out of sync with the time of day, which is related to various diseases that have become social problems.

To understand the circadian rhythm of a person's body, a common method is to collect blood and examine temporal changes in hormone components. Measuring CBT is also an effective method. As shown in **Fig. 1(b)**, if there is no shift between the body's rhythm and time of day, CBT begins to decrease a few hours before sleep and begins to increase in the second half of the sleep cycle. However, if the body's circadian rhythm and the timing of sleep and waking up shift due to irregularities, the quality of sleep will deteriorate. Such a state is called "social jet lag," since the person feels like they have jet lag. If this state continues, it will lead to sleep disorders, such as trouble sleeping, light sleep, difficulty getting up in the morning, and sleepiness during the day, which adversely affect physical and mental health as well as social activities [2]. The circadian rhythm can be improved by external stimuli such as light irradiation. Therefore, if it were possible to measure CBT without burdening the individual and easily understand a person's circadian rhythm, as shown in **Fig. 1(c)**, it would be possible to build a healthcare



(a) Core and CBT

(b) Circadian rhythm visualized from CBT measurement

(c) Example of a healthcare system using CBT measurement

(d) Scenarios when to measure CBT

Fig. 1. Core body temperature (CBT) and how to use it.

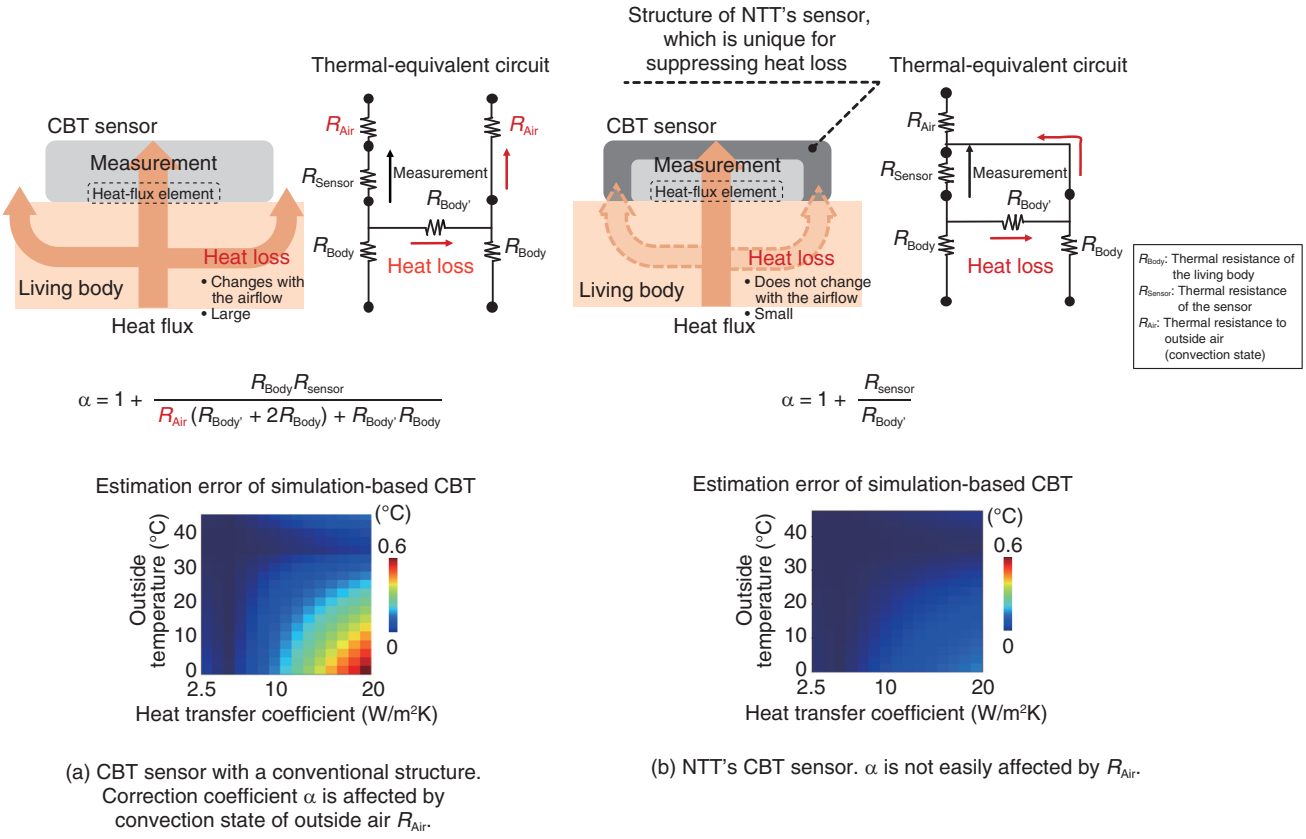
system tailored to each person. Accordingly, measuring CBT should contribute to various scenarios related to circadian rhythms, such as sleep management, nursing care, and labor management, as shown in **Fig. 1(d)**.

NTT has been developing highly accurate, low-burden CBT sensors for detecting slight variations in CBT (i.e., about 1°C in a day). In this article, we introduce current methods of measuring CBT, the principle of our non-invasive sensor for measuring CBT, and the current progress in our research.

2. Current methods for measuring CBT and challenges

Methods for measuring CBT can be divided into two categories on the basis of their degree of invasiveness. The first category includes methods of inserting a thermometer into a body cavity and measuring the temperature. A sublingual thermometer is used to measure CBT by inserting it under the tongue and keeping the mouth closed for a certain period so that the measurement is not affected by breathing or eating. An eardrum thermometer is used to measure the eardrum temperature by measuring the infrared rays emitted from the eardrum with a sensor inserted into the ear. Since the temperature of the eardrum reflects the temperature of the nearby carotid artery, it is possible to measure CBT. During surgery, for strict control of CBT, rectal temperature is measured via an inserted sensor, and pulmonary-artery temperature is measured using an inserted catheter. Since these measurement methods are invasive, the thermometer is not easily affected by the external environment, and the measured temperature is reliable. Since the thermometer is inserted into the body, however, it places a heavy burden on the patient and requires caution in terms of hygiene.

The other category includes methods of measuring temperature through contact with the surface of the



(a) CBT sensor with a conventional structure. Correction coefficient α is affected by convection state of outside air R_{Air}.

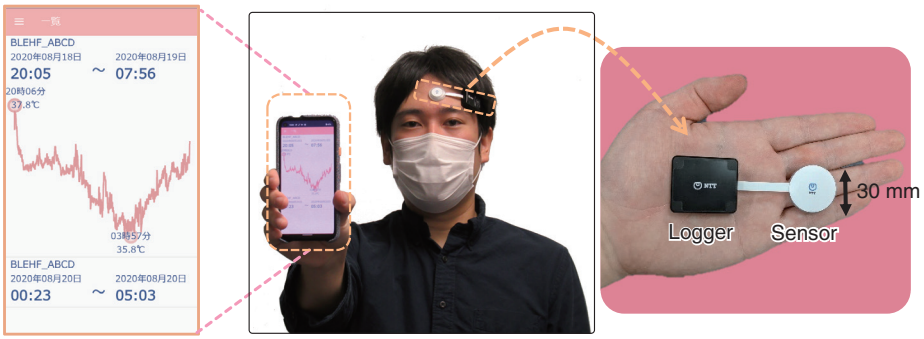
(b) NTT's CBT sensor. α is not easily affected by R_{Air}.

Fig. 2. Structure and estimation error of CBT sensor.

body. Although it is hygienic, the thermometer comes into contact with the external environment, so the surface at which temperature can be measured is limited. An axillary thermometer is used to measure a temperature reflecting the CBT by closing the armpit tightly around the thermometer and keeping it there for about five minutes [3]. However, it is difficult to maintain this state for a long time. Therefore, a sensor using a method called the zero heat flux method (ZHFM) can be used to measure CBT even if the thermometer is attached to the body and exposed to the external environment. With this method, a sensor is affixed to the forehead, and CBT is measured by applying heat (via a heater inside the sensor) to cancel the heat flow (heat flux) from inside to the surface of the body. The sensor used with ZHFM requires a relatively large amount of electric power because it involves heating a living body. In addition, the environment in which it can be used is limited, so it is used to control CBT only during surgery. In light of these circumstances, as a method with low power consumption and few restrictions on the usage environment, and a sensor that measures the heat flux by being affixed to the surface of the body and estimates CBT without heating is needed. However, measurement errors likely occur with sensors that measure heat flux due to changes in the external environment (such as airflow variation) and changes in the person's sweating. Accordingly, NTT is attempting to solve this problem by using a non-invasive method of measuring CBT, which is less burdensome for the individual having his/her temperature taken, involving affixing a sensor to the surface of the body.

3. Non-invasive measurement of CBT and features of our sensor

The non-invasive method for measuring CBT simply by affixing a sensor on the surface of the body (skin) is outlined in **Fig. 2**. CBT is manifested as skin temperature from the CBT region in the core of the body through biological tissues. Compared with CBT, the skin temperature is lower under normal, comfortable conditions owing to the dissipation of



(a) Measurement-app screen (b) When the sensor is affixed (c) NTT sensor

Fig. 3. CBT sensor researched and developed by NTT.

heat to the outside air. To convert skin temperature measured on the surface of the body to CBT, it is necessary to determine the temperature distribution from the region of the body corresponding to CBT to the surface of the body where the CBT sensor is affixed. In other words, the true CBT is estimated by calculating how much the skin temperature has dropped from the CBT. This is called the heat-flux method [4]. In previous research examples of a CBT sensor using the heat-flux method, as shown in Fig. 2(a), CBT could be accurately estimated in an experimental environment without air flow.

In environments where people live, there is rarely no airflow, so convection always exists. When a CBT sensor is affixed to the surface of the body, the skin temperature in the area covered by the sensor is higher than that around the sensor (which is not covered). This state causes heat to flow outwards from the sensor, as shown with the arrows in Fig. 2(a). This *heat loss* is heat that cannot be measured in the sensing area, thus causing errors in CBT estimation, as shown in Fig. 2(a). One method of estimating CBT is calibrating a correction factor (α) in advance as the ratio of heat flux (measured using the heat-flux sensor) to heat loss [5]. However, α is also affected by changes in convective conditions, which also cause estimation errors.

With such estimation errors in mind, we developed a sensor for which α is less sensitive to convective conditions [6]. The structure of this sensor is outlined in Fig. 2(b). In a conventional CBT sensor, the leaked heat flux is directly dissipated to the outside air without going through the sensor, and α depends on the convection state. Our sensor is surrounded with a high-heat-conduction material that allows heat to pass through easily, and the leaked heat flux passes through the high-heat-conduction material, merges with the heat flux measured with the heat-flux sensor, and dissipates to the outside air. Therefore, α is independent of the convective state, and errors in CBT estimation can be reduced. The structure of this sensor is called the heat-loss-suppression structure. By optimizing the shape of this structure and minimizing heat loss, our sensor is smaller and is more accurate than a conventional CBT sensor. As shown in Fig. 2(b), using this optimized sensor makes it possible to suppress errors in CBT estimation to within 0.1°C, even when the airflow rate is 5 m/s, which is stronger than the airflow rate of an air conditioner.

4. Example results of measuring CBT by using our developed sensor

Our CBT sensor with the heat-loss-suppression structure is shown in **Fig. 3**. The sensor part (white probe) has a diameter of 30 mm, which is about the same size as a plastic-bottle cap, and a thickness of 5 mm, which is one-third that of the cap. Skin temperature and heat flux measured with the sensor are digitally converted by the logger, transferred to the measurement app via Bluetooth, and recorded.

Measurement results from an experiment in which the CBT sensor was affixed to a person's body is shown in **Fig. 4**. The sensor was affixed to the forehead of two different participants in two experiments: one in which air was blown by a fan at the participant, and one in which the participant performed low-intensity exercise (on an exercise bike). In both experiments, the reference temperature (of a commercially available eardrum sensor) highly

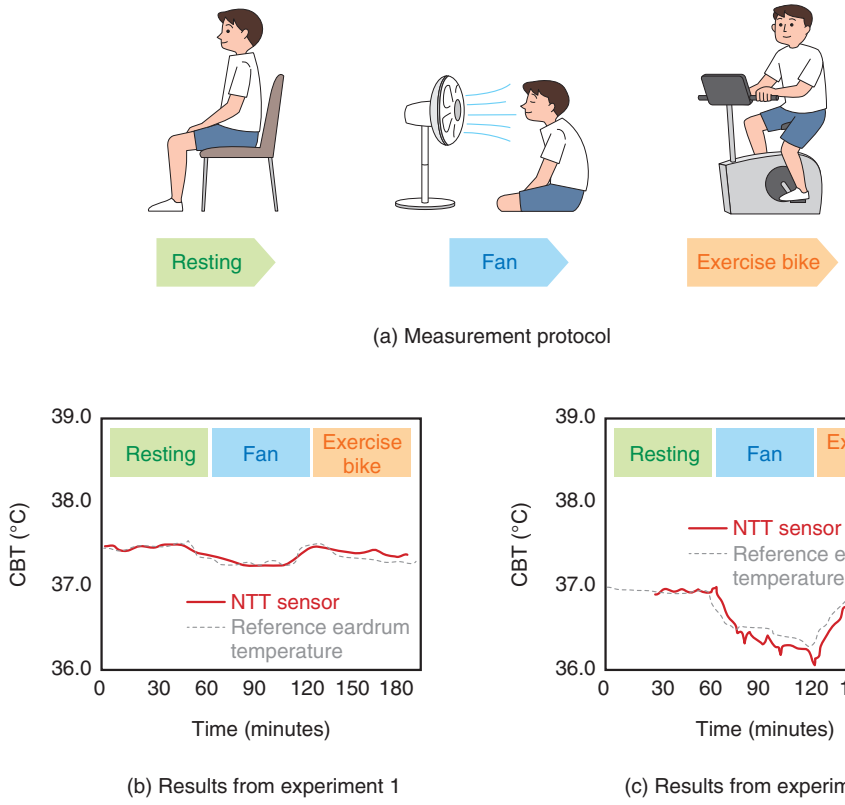


Fig. 4. Example of measuring CBT ((b) and (c) are results from different participants).

correlated with the temperature measured using our senor. These results indicate that CBT can be accurately measured with this sensor even in an environment in which convection exists, such as in a room cooled with an air conditioner.

5. Future prospects

In this article focusing on implementation of a noninvasive CBT sensor that can be simply affixed to the surface of the body, we introduced a method for estimating CBT from heat flux. If daily high-precision CBT measurement is possible, which had been difficult, it can be used for health-management systems and new medical treatments such as chronopharmacology. If it becomes possible to visualize the body's circadian rhythms from fluctuations in CBT and understand deviations from daily rhythms, it will be possible to implement applications that maintain the body's circadian rhythms appropriately by controlling the environment in cooperation with smart homes and other devices.

For long-term daily monitoring, usability, such as wearability and continuous measurability, as well as connection with smartphones for data collection and visualization are key factors. We will continue research and development on long-term continuous measurement using a device that integrates a sensor and logger.

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New Technology for Measurement and Analysis of Biological Sounds and Electrocardiographic Signals—Toward Early Detection of Heart Disease and Rehabilitation by Using Personal Heart Modeling

Masahiro Nakano, Ryohei Shibue, Kunio Kashino, Shingo Tsukada, and Takayuki Ogasawara

Abstract

Biological sounds and electrocardiographic signals are important for understanding the physical and psychological state of a person. In this article, signal-processing and machine-learning technologies involving measuring biological sounds by using a wearable acoustic-sensor array, called a telestethoscope, as well as new measurement and analysis technology, i.e., tensor electrocardiogram using hitoe™, are introduced. The possibility of early detection of diseases by using such personal heart modeling and its application to post-onset rehabilitation are also discussed.

Keywords: telemedicine, tensor electrocardiogram, wearable devices

1. Estimating the state of mind and body through biological sounds

The biological information obtained from measuring the living body reflects the function, morphology, and dynamic characteristics of the living body. We are researching and developing the concept of *bio-digital twins* to improve people's well-being by, for example, early detection of diseases. With a bio-digital twin, various types of biological information as signals are captured, and signal-processing and machine-learning technologies are used to model the physical and mental states of each person on the basis of the observed signals. Initiatives that focus on the sounds generated by living organisms are first introduced.

1.1 Telestethoscope

Doctors and nurses use auscultation to determine the presence or absence of abnormalities and the degree of urgency. Skilled medical practitioners can visualize in their minds the generation and transmission of biological sounds such as breathing, movement of heart valves, and blood flow. Inspired by such auscultation by medical professionals, we are conducting research and development on a wearable device called the telestethoscope (see **Fig. 1(a)**).

The telestethoscope is used for acquiring biological sounds (acoustic signals) from multi-channel microphones and electrocardiograms (ECGs). The acquired acoustic signals and ECG can be sent to a remote terminal via a network. Sounds from various points on the wearer's body can be heard by touching the

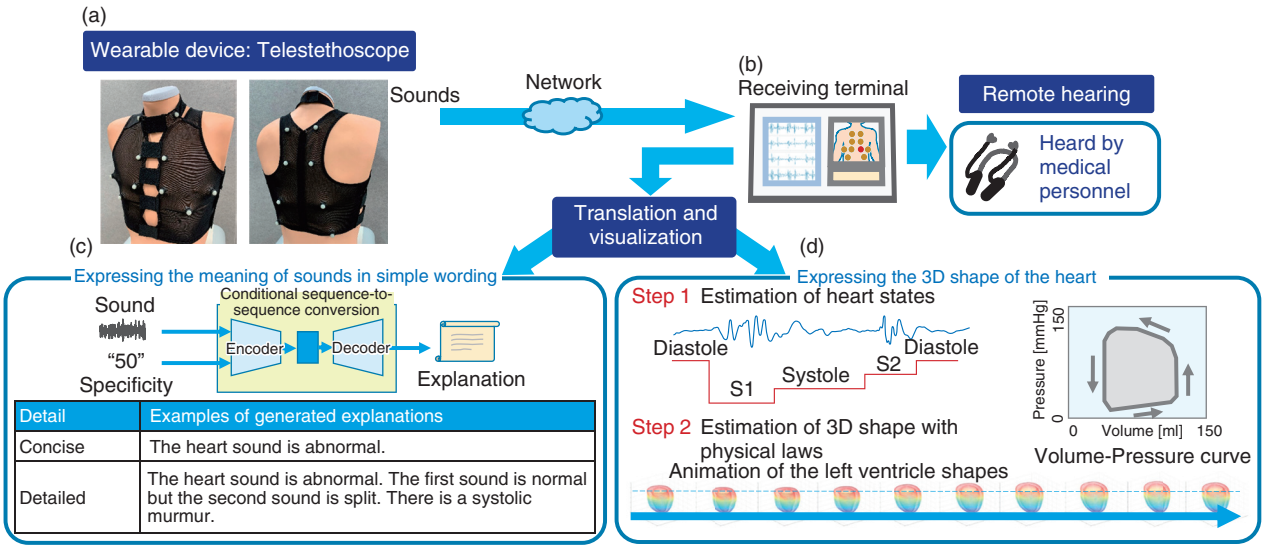


Fig. 1. System overview of telestethoscope. (a) Telestethoscope wearable device, (b) remote auscultation, (c) automatic sound-description generation, and (d) visualizing estimated 3D cardiac motion in accordance with the estimated heart states.

screen of that terminal. An overview of the telestethoscope is shown in Fig. 1.

The telestethoscope will allow medical personnel to listen to acoustic signals of patients remotely without having to come into contact with patients; therefore, it will be useful for examining patients with infectious diseases and assessing the urgency of patient care from a distance (e.g., when the patient is at home or in a rural area) (**Fig. 1(b)**). Since it is possible to record and share biological sounds, it is also possible to repeatedly auscultate offline or chronologically study the status by comparing current and past sounds. In addition to the above use by medical professionals, we are also researching its use by the general public for self-healthcare, as described below.

1.2 Adding descriptive text to heart sounds by using the telestethoscope

It is not easy for non-specialists to understand the information about living organisms by simply listening to biological sounds. However, signal processing and machine-learning technology makes it possible to convert biological sounds into a form that is easy for many people to understand. Therefore, we are investigating converting (translating) biological sounds directly into simple wording (**Fig. 1(c)**).

The most-straightforward means of explaining biological sounds would be to classify them as "normal" or "abnormal." However, if a person's sounds are classified as "abnormal," a more-detailed explanation may be needed. For example, it would be useful to know what abnormalities are present and whether the person in question should go to the hospital immediately. To address this issue, we previously proposed a method called *conditional sequence-to-sequence caption generation*, which allows the user to specify a numerical value called *specificity* that represents the level of detail of the description to be generated [1]. For example, if the heart sounds and a large number as a desired level of detail are input into the system, a detailed explanation can be output.

1.3 Estimating health status via video images from heart sounds acquired from the telestethoscope

Another means of converting biological sounds into an easy-to-understand form is to generate moving images that represent biological functions in real time (**Fig. 1(d)**). We have attempted to reconstruct the movement of the heart from the sound of the heart. A normal heart moves in a cyclic fashion in which the transitions occur in the following order: atrial systole, isovolumic systole, ejection phase, isovolumic diastole, and filling phase. We therefore aim to estimate the transitional state of the heart from measuring heart sounds then estimate and reconstruct the movement of the heart in three dimensions (3D). Since the

heart pumps blood around the body, a specific physical relationship between its pressure and volume is maintained through the state transitions. Focusing on this physical relationship, we devised a method of constructing a 3D moving image. This method uses the physical relationship to improve the accuracy of cardiac motion estimation by restraining it in accordance with the state transition, which is estimated from the heart sounds [2].

Accurately estimating and predicting the physical and psychological state of an individual from easily observable biometric information, such as sound, will necessitate many other innovations. We will continue to research and develop signal-processing and machine-learning technologies for measuring biological functions and dynamics from multiple perspectives, such as sound information and electrocardiographic information, as described below.

2. Wearable 3D ECG device using new lead system and ECG analysis method called tensor ECG guided by the new system

To determine the physiological function of the heart, ECGs are widely used in, for example, diagnosis at medical institutions, vital-sign monitoring, medical examinations, and automated external defibrillators. With advances in information and communications technology, such as the Internet and smartphones, as well as in information-processing technologies, such as machine learning, ECGs are being applied in new fields such as artificial-intelligence-guided healthcare. Due to the increase in cardiac diseases in the *super-aging society*, a society whose population aged 65 or older is over 21%, the need for home care and telemedicine using electrocardiography is rapidly increasing. Taking advantage of our experience in developing a wearable ECG device using hitoe™, we are developing a wearable device for continuous measurement of ECGs and an ECG analysis method by combining medical knowledge on clinical ECGs with recent information-processing technology [3].

2.1 3D ECG induction suitable for long-term recording in wearable device

ECGs are analyzed on the basis of their potential difference (scalar quantity) and shape (pattern), which are obtained from multiple bioelectrodes placed at specified points (standard 12 leads) on the surfaces of the extremities and chest. As a method of recording electrocardiographic potential more three-dimensionally, a vector ECG (which uses a three-axis Cartesian-coordinate system) involves using electrodes on the chest, head, and lower extremities and a resistance-correction circuit. Since both standard-12-lead and vector ECGs involve using electrodes on the extremities, they are easily affected by body movements, so they are basically recorded while the patient is in a resting state. However, electrodes attached to the chest are less affected by body motion and can produce relatively large cardiac potentials, so they are used for Holter ECG monitors (portable devices for cardiac monitoring), exercise-load, and sports ECGs.

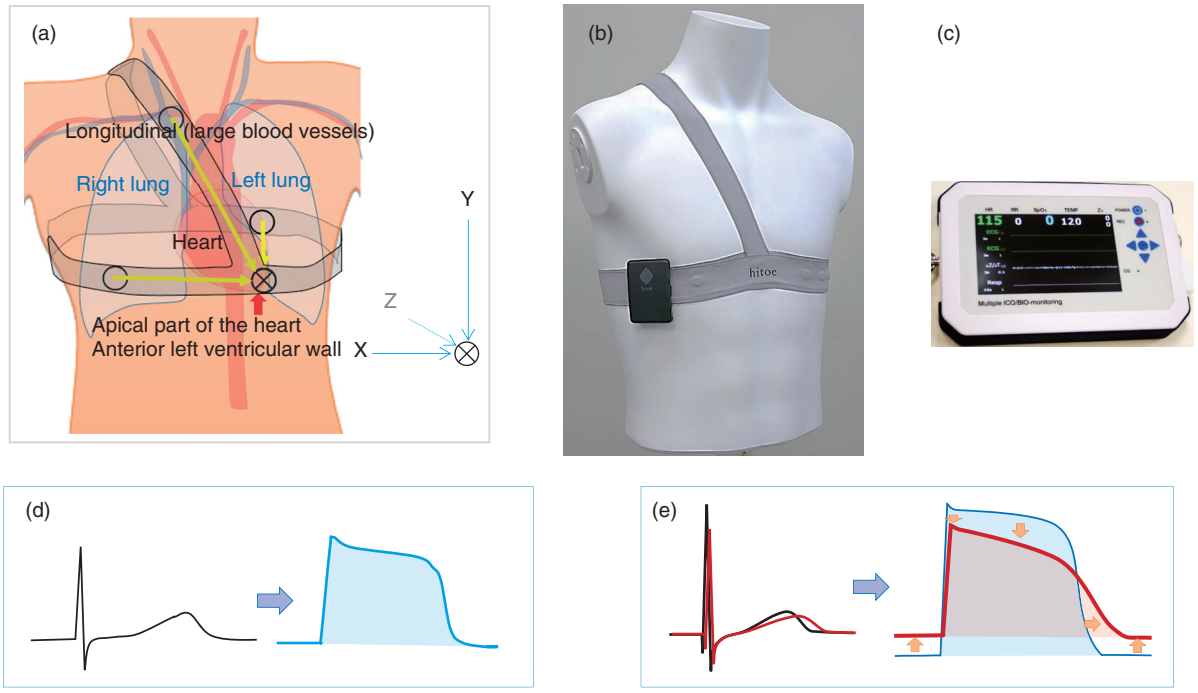
For long-term stable recording of a 3D ECG, we devised a wearable devise for measuring ECG with its reference point set in the apex region of the heart (i.e., on the left anterior wall, where the heart is closest to the thorax) and with counter poles in three linearly independent directions (**Fig. 2(a)**) [4]. By bipolar induction[*1] generated by placing two horizontal leads on opposite sides of the thorax and vertical leads on the upper right precordium in line with the electromotive-force base axis[*2], 3D electrocardiographic potential can be stably recorded (**Fig. 2(b)**). The electrodes and wires are integrated into an elastic belt that can be easily attached by simply tightening the shoulder and waist parts of the belt. We have also developed a non-invasive cardiac polygraph with hemodynamics for simultaneously measuring cardiac output and deep vascular pulse waves (**Fig. 2(c)**).

2.2 New method for analyzing ECGs: tensor ECG

Abnormalities in ECGs are shown as not only a standardized abnormal waveform (pattern) but also as a slight distortion of the shape or change in potential. A method of quantitatively evaluating such atypical ECG abnormalities has not been developed. We are currently designing individual criteria for specific diseases and special patterns to identify them. Regarding the collective action potential of the myocardium, the electromotive force of the cardiac potential has three plateau phases with continuous depolarization,

*1 Bipolar induction: An ECG records the flow of electricity in the heart, and induction is the process of creating a flow of electricity from a negative electrode to a positive electrode by attaching electrodes across the heart. Bipolar induction is a method of acquiring an ECG by using two electrodes.

*2 Base axis of electromotive force: Since the heart is a 3D structure, its electrical charge continuously changes three-dimensionally. An ECG can be regarded as a recording of the electromotive force generated throughout the heart, and the direction of the electromotive-force vector is called the base axis.



(a) Placement of electrodes for linearly independent triaxial bipolar induction with respect to the apex (anterior wall of the left ventricle). The positions of the heart, lungs, and major vessels of the longitudinal axis are shown.
(b) Belt-type Holter ECG for 3D induction method.* Multiple electrodes are placed on the inside of the right shoulder and waist belts.
(c) A measurement device for simultaneously measuring 3-channel ECG and impedance blood flow via Bluetooth wireless communication.*
(d) Cardiac ECG, which is the source of the ECG recorded on the body surface (black), is the action potential of the myocardium (blue), characterized by a trapezoidal plateau phase. The action potential of the myocardium is estimated from the ECG by signal processing.
(e) The ECG of heart failure (red) may slightly differ from normal (black). Conversion from ECG to myocardial action potential reveals this distortion.
* Unapproved medical equipment

Fig. 2. Overview of tensor ECG: a new induction and analysis method.

whereas the cardiac potential at the body surface does not usually show such a plateau. We use the molecular-biology and physiological constraints of the membrane potential of each period (from phases 0 to 4) of the action potential to estimate the collective action potential of the myocardium from the electrocardiographic potential on the body surface (i.e., an inverse problem) (**Fig. 2(d)**). From the conversion of electrocardiographic potential to action potential, atypical distortions are magnified and made clearly visible (**Fig. 2(e)**). We are examining whether the parameters (tensor[s]) obtained during the conversion to action potential of the myocardium can be used as indicators for quantifying and uniformly evaluating complex abnormal patterns and minute distortions in ECGs. We anticipate that tensor ECG for multi-mode data measurement and analysis will be useful in diagnosing arrhythmias associated with heart failure, ischemic heart disease, and sudden cardiac death.

3. Application to rehabilitation using wearable devices

Wearable devices are useful not only for early detection and accurate diagnosis of diseases but also after the onset of disease. One example of a wearable device is one for improving rehabilitation quality we have been developing and medically validating with Fujita Health University and Toray Industries, Inc. since 2017 [5]. Taking stroke rehabilitation as an example, the more opportunities for rehabilitation (exercise training) after the occurrence of a stroke, the better the outcome can be expected [6]. However, rehabilitation with therapists is limited, so stroke patients are encouraged to be as active as possible in their daily lives by getting out of bed or doing rehabilitation exercises on their own. However, it is difficult for a patient with a one-side-paralyzed (hemiparetic) body to exert vigorous effort on their own, so they need support to achieve a better recovery.

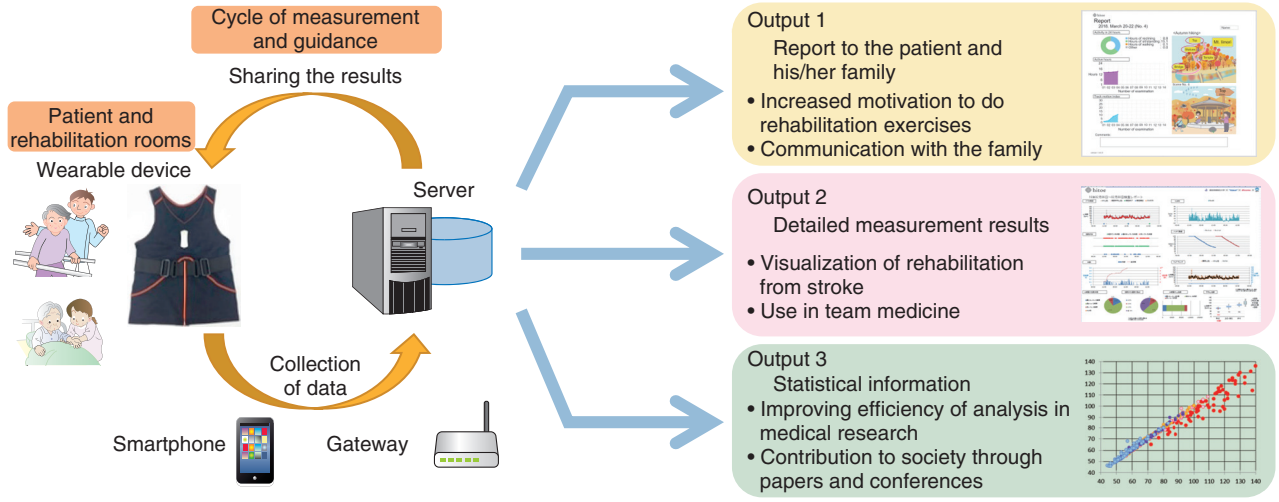


Fig. 3. Overview of the rehabilitation support system.

Against this background, we developed a wearable-device that enables precise monitoring of activities of a stroke patient on a 24-hour basis (**Fig. 3**). For example, a hemiparetic patient wears our device, which he/she can put on and take off by him/herself, and data are automatically collected on a server through a relay such as a smartphone or gateway. The device includes an algorithm for processing data for (i) advanced downsampling that avoids overloading the network of hospital facilities while preserving the characteristics of the patient's activity and (ii) imputation processing assuming partial data loss. Medical validation of the index obtained by these processes is also underway.

This device is used on the basis of three types of outputs. The first is a report for the patient and their family. The recovery process can be clearly conveyed through numerical records of the gradual increase in the time spent in active movement. The illustrations change as the patient progresses, so the patient and his/her therapist can discuss the progress made after each session, which will lead the patient to the next exercise. The second output is the detailed measurement results used in medical-team meetings. Medical-care providers working with a large number of patients cannot keep track of specific individuals. However, on viewing the 24-hour record output from the device, the entire team can share changes in a certain patient's daily activities. The third output is listed information based on measurement data.

Regarding medical research, facts are revealed by verifying statistical certainty derived from a large number of measurement results. However, the amount of activity data over a 24-hour period is large; therefore, we designed a system for automated preprocessing so that it can be easily used in medical research. The system also supports the 6-minute walk test, which is widely used in rehabilitation studies. This allows the results of 24-hour activity monitoring to be easily compared with previous studies. We expect this will lead to new insights in rehabilitation research. The system has been commercialized and is being used for medical research. We believe that it will further contribute to better patient recovery through combining it with advanced technologies such as machine learning.

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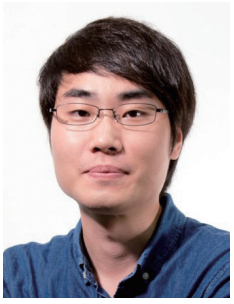

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Bionics Technology for the Future of Medicine and Health

Riku Takahashi, Aya Tanaka, Masumi Yamaguchi, and Yukio Koike

Abstract

Bionics is a discipline that elucidates the structure and function of living organisms—by using engineering techniques and theories—and applies that knowledge in the form of new technologies. Developing technologies that interactively connect biological and engineering systems is key in creating a bio-digital twin and developing technologies for medicine and healthcare. In this article, bionics technologies developed by NTT Basic Research Laboratories and NTT Service Evolution Laboratories are introduced.

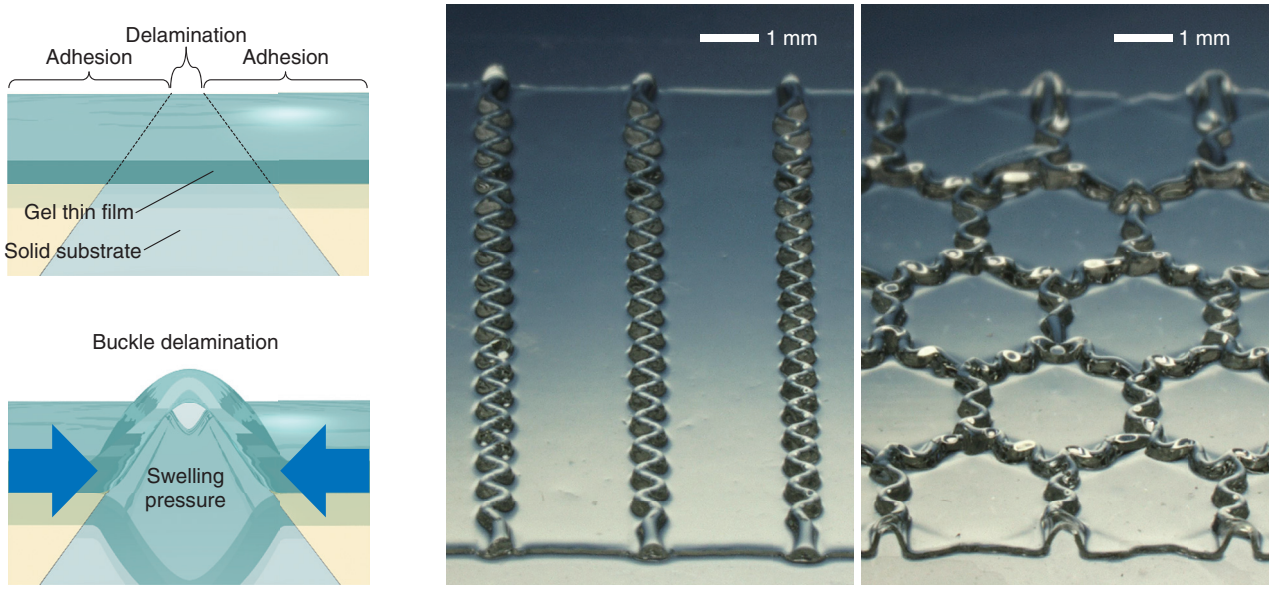
Keywords: bionics, microphysiological system, cybernetics

1. Approaches to bio-functional device technology for acquiring biometric information

Bionics is currently trending in two directions. One direction is from biology to engineering, namely, to artificially reproduce the functions and structures of living organisms. Advances in semiconductor-microfabrication technology and three-dimensional (3D) printing technology have made it possible to reproduce surface shapes and 3D structures that mimic living organisms even on the nano- and micrometer scales. Microphysiological systems (MPS) have been attracting attention that combines such microstructures with various cells to create functions and structures of organs. By creating a scaffold structure for cell culture by microprocessing, it is possible to artificially reproduce the tiny spaces in the living body and the physiological environment for mechanical stimulation by, for example, blood flow and stretching movement. Therefore, higher-order in-vivo functions that cannot be implemented using conventional culture methods should be expressed in vitro, enabling highly accurate and multifaceted observation and evaluation. Such in-vitro devices that imitate the heart, liver, kidneys, and other organs have been reported [1]. The construction of a fully reproduced model of a single organ or of interaction between different organs by linking multiple organs has unlimited potential. Such a model could be applied to drug discovery, such as accurate prediction of pharmacokinetics in relation to particular organs. It could also be used to enable the acquisition and analysis of personalized biological information at the molecular, tissue, and organ levels, which are tasks necessary to create a bio-digital twin.

Most MPS devices are consist of a rubbery material called polydimethylsiloxane, which is highly processable, transparent, and oxygen permeable. To stably express higher-order functions in cells for a long period and interact with the outside world through molecules secreted and absorbed by cells, it is important to approach the biological environment from the material level. With this in mind, NTT Basic Research Laboratories focused on hydrogel, a material that is more like living organisms since it is a soft material that contains a lot of water and can stand on its own as a thin and hollow tubular structure like blood vessels or intestinal tubes. An example application of hydrogel is in contact lenses.

In a hydrogel, polymers (consisting of low-molecular-weight compounds) and aggregates of molecules form a network structure like a jungle gym, which can retain a large amount of water inside it. This structure is similar to an extracellular matrix, which



(a) Schematic diagram of the formation of buckle-delaminated structure

(b) Optical micrograph

Fig. 1. Formation of buckle-delaminated structure of hydrogel thin film.

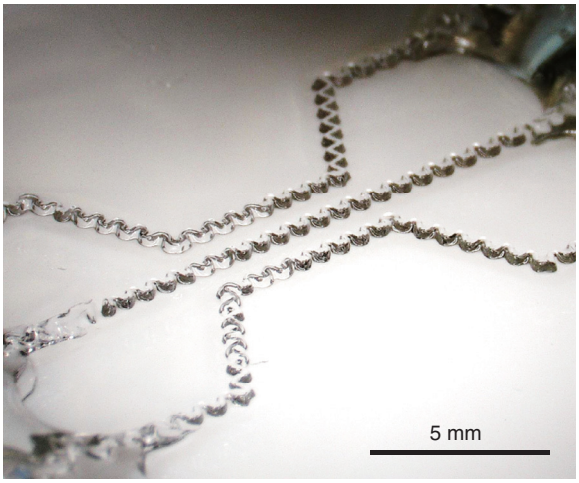
is a scaffold of cells in the living body, and exhibits high biocompatibility. It has unique functions not found in ordinary solid materials, such as water-mediated permeability of small molecules and volume changes due to inflow and outflow of water. In this article, we introduce the technology for processing hydrogels for implementing MPS devices that can reproduce the dynamics of an in-vivo environment, such as inflow and outflow of material and shape change.

2. Formation of 3D structure of hydrogel on the basis of buckle delamination

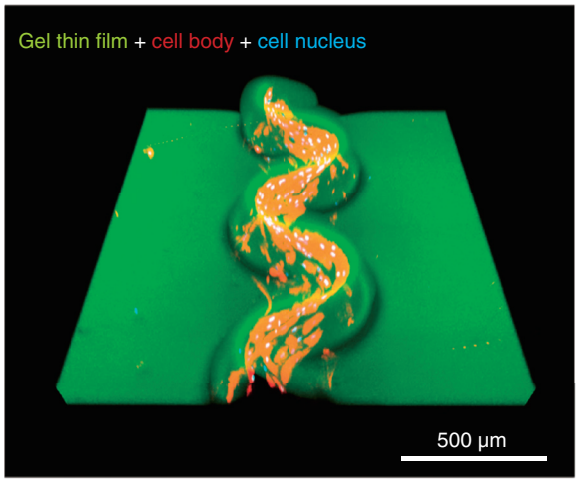
A physical phenomenon called buckle delamination was investigated as a means of fabricating a hydrogel. When a piece of paper placed on a desk is compressed from both ends, the center of the paper is raised and curved, transforming it into an arch-like structure. This phenomenon is referred to as buckle delamination, namely, the material buckles and delaminates from the substrate underneath it. We previously developed a method of applying this phenomenon to form hydrogel thin films [2]. Examples of such hydrogel thin films are shown in **Fig. 1**. The first step of the film-formation process is to define the delamination points by patterning adhesive molecules on a solid substrate by using conventional photolithography. The hydrogel is then formed on the substrate in a manner that produces a hydrogel thin film bonded to the substrate in a certain pattern. The hydrogel is then exposed to water, which causes it to swell as it absorbs the water. This water absorption compresses the hydrogel thin film by swelling pressure and induces buckling and delamination, specifically at the non-adhered parts of the body (Fig. 1(a)). The structure to be formed is controlled by physical parameters, such as hardness, thickness, and swelling degree of hydrogel, and the geometric structure of non-adhered body parts, and it can be processed into various 3D shapes (Fig. 1(b)).

3. Future developments regarding this direction

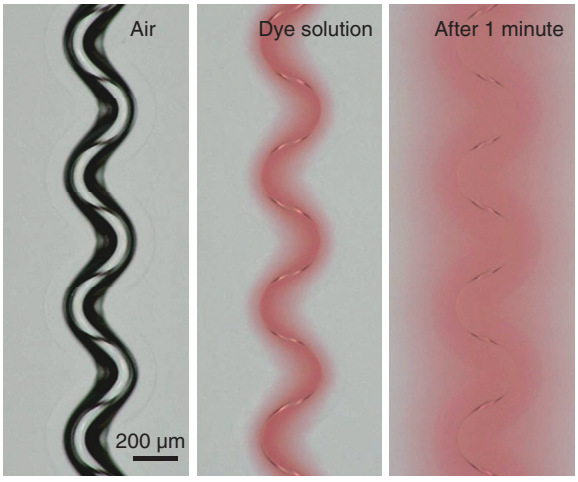
Application of a device using three features of the above hydrogel-thin-film technology is shown in **Fig. 2**. (1) A buckle-delaminated structure can be induced with good reproducibility by drawing a 2D pattern of the desired bonded and non-bonded regions on a large area. It is thus possible to freely create meandering, parallel, and merging flow-channel structures, which can be used as microfluidic devices based on hydrogel thin films (Fig. 2(a)) [3]. (2) The hetero-structure of the device (i.e., hydrogel and solid



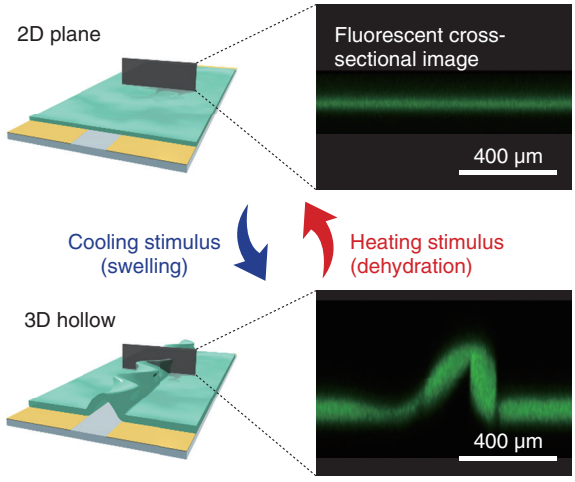
(a) Hydrogel fluidic device



(b) Fluorescence image of cultured cells



(c) Dye diffusion from inside the flow channel



(d) Shape control using stimuli-responsive gel

Fig. 2. Deployment of device with buckle-delaminated structure.

substrate) allows each function of the device to be designed individually. Cell culture in the flow channel and material diffusion outside the channel are possible (Figs. 2(b) and (c)). By implementing sensor elements on the solid-substrate side, it should be possible to develop devices that can measure the environment in real time in a manner that mimics a living body. (3) Since the processing method is based on a universal physical phenomenon, it can be adapted to various types of hydrogels, and functions can be added. By using a stimuli-responsive gel (the water content of which can be controlled in response to thermal stimuli) as a base material, it is possible to dynamically control the structure in response to stimuli (Fig. 2(d)). By developing and combining these elemental features, it is believed possible to develop technology that can acquire multifaceted data while reproducing biological functions on a device.

4. Initiatives concerning cybernetics technology for supporting people with disabilities

The other direction in bionics is engineering to living organisms. The purpose behind this direction is to apply communication theory and control theory to

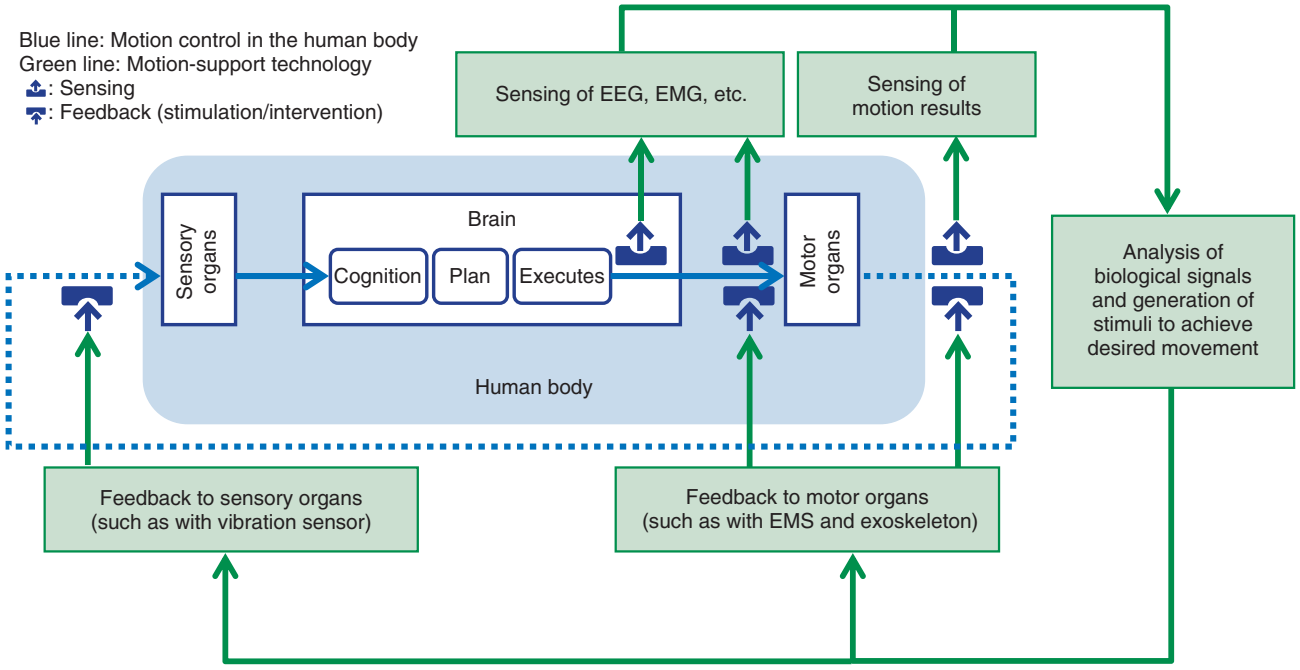


Fig. 3. Motion control and assistive technology for the human body.

the mechanisms of information transmission and control within the body. In particular, cybernetics [4], proposed by Norbert Wiener in 1948, which has continued to be important, is the concept of handling communication and control in living organisms and machines in a unified manner. At NTT Service Evolution Laboratories, we are paying renewed attention to this concept. Regarding our initiatives concerning cybernetics technology, we are developing technologies to support and extend human motor skills.

Regarding motor control in the human body, stimuli received by the sensory organs are perceived and recognized by the brain. Then, motion instructions issued according to the action plan in the brain are transmitted to the motor organs, which executes the plan by contracting the muscles that make up the motor organs (**Fig. 3**). This process is repeated as a cycle; namely, the result of the action received by the sensory organs is taken as a new stimulus.

We are intervening in this cycle by using the following methods to understand and improve motor status: (i) sensing biological signals (such as electroencephalography (EEG) and electromyography (EMG)) and motion results and (ii) providing feedback (so-called stimulation and intervention) to the sensory and motor organs via tactile stimulation such as vibration, electrical muscle stimulation (EMS), and the exoskeleton. We have started to analyze the sensed biological signals and generate feedback to achieve the desired motion.

5. Support and extension of motion by using biological signals

We now introduce the concept of motion support and augmentation by sensing, analyzing, and feeding back biological signals. Our goal is to create a world in which anyone can more skillfully control their own motor functions while executing daily activities and various skills on the basis of the movements of others (experts) and their own past movements. In other words, we want to temporarily or permanently expand people's ability by reproducing and experiencing movements. Two example possibilities are (i) reproduction of the movements of experts and effective training by repeating those movements and (ii) rehabilitation tailored to the current physical condition of patients on the basis of their experience of exercise when they were younger.

Motion support for a tremolo performance (a technique by which notes that are far apart are played alternately) on piano [5] is given as an example (**Fig. 4**). Beginners play while focused on moving the fingers, while experts play while focused on rotating

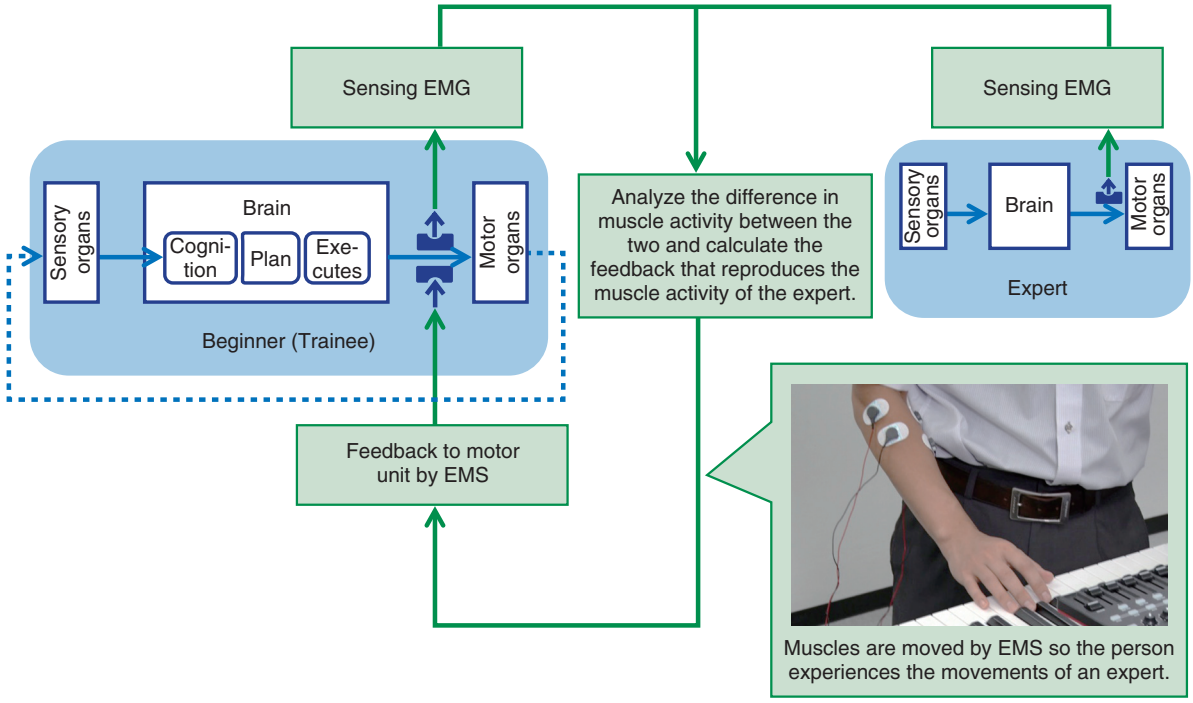


Fig. 4. Example of motion support through acquisition and analysis of biological signals and feedback.

the wrist. On the basis of that consideration, EMG is sensed as the biological signals of a beginner (trainee) and expert, and the difference in muscle activities between the two (e.g., the difference in strengths of each muscle type) is analyzed by comparing the two signals. Feedback to reproduce the muscle activity of an expert (e.g., muscle contraction by EMS) is then calculated. The calculated muscle activity is then fed back to the beginner's (trainee's) body.

The photo in Fig. 4 shows that the hand of the user is moved by presenting EMS to the muscles that rotate the wrist (the supinator and pronator teres muscles) to enable the user to experience the movements of the expert. We are currently evaluating whether effective training can be achieved through this experience. Although the example shown in the figure is an initiative focusing on myoelectricity, we are also studying biological signals other than myoelectricity, such as brain waves.

6. Future developments regarding this direction

Various exercises, such as stretching, grabbing an object, pressing a button, standing, and walking, are important in daily activities, social participation, and self-expression. However, some people are forced to live with limited mobility due to disabilities or aging, and we have high expectations for supporting the mobility for people with such limitations.

There are various approaches of sensing (e.g., using EEG and EMG) and feedback (e.g., using EMS and exoskeletons), and it is assumed that they will become more sophisticated. For example, technologies and products (e.g., prosthetic hands) that are expected to function reliably for specific body parts and for specific motions during daily use as support for disabled people must be extended to cover more body parts and accommodate complex motions. As that requirement is satisfied, the amount of biological sensing information and control information used for feedback will become more complex, and it will be necessary to handle such information in a coordinated manner, as described in the previous section.

At NTT Service Evolution Laboratories, we have been working on bio-sensing technologies on the basis of signals such as EMG [6], feedback technologies using tactile stimulation and EMS, and support for people with disabilities.

By taking advantage of our accumulated technological strengths, such as bio-sensing and feedback technologies, we believe that we can assist and support the expansion of application to other body parts

and handling of complex movements from the perspective of information and communication technology. We will continue to study the application of cybernetics technology to training and rehabilitation for supporting people with disabilities.

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Disaggregated Computing, the Basis of IOWN

Akira Okada, Seiji Kihara, and Yoshikatsu Okazaki

Abstract

To achieve IOWN (the Innovative Optical and Wireless Network), we need advanced computer systems that can efficiently process huge amounts of data compared with current capabilities. To meet this demand, NTT is studying an innovative computer architecture, called *disaggregated computing*, that makes maximum use of photonics-electronics convergence technology. This article describes the overall outline and basic concept of this new computer architecture.

Keywords: IOWN, photonics-electronics convergence, computer architecture

1. Introduction

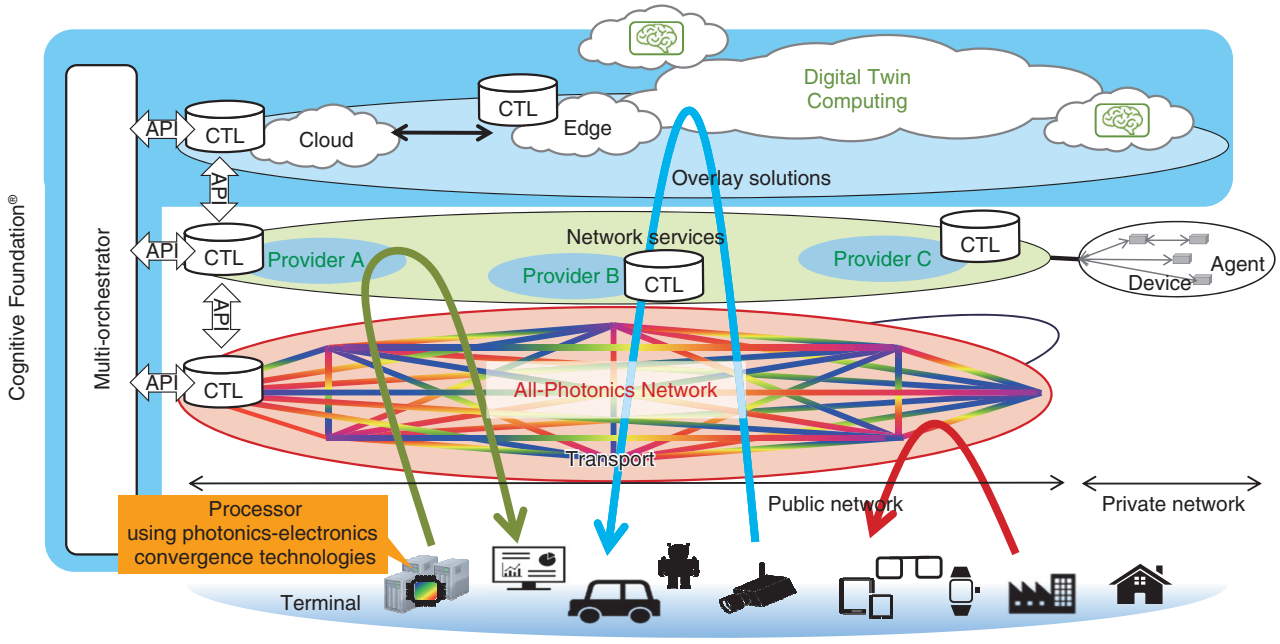
Almost everything is connected to networks, and a vast amount of data from them is drastically changing social, economic, and cultural activities. By interconnecting a huge amount of data, it is important to create new value that cannot be obtained only from individual data in such a smart society. To achieve this, not only a broadband network, which transfers data at unprecedented high speed, but also an information processing system with a high processing capacity that is beyond today's technologies is required.

To achieve such a smart society, NTT has proposed the Innovative Optical and Wireless Network (IOWN) [1]. The IOWN Global Forum was founded in 2020 [2] to accelerate innovation of a new communication infrastructure to meet our future data and computing requirements through the development of technologies, frameworks, and specifications. IOWN is a broad vision that includes innovative networks and computing systems boosted by photonics technologies and services provided using them.

2. Computing power for IOWN

Figure 1 shows the conceptual diagram of IOWN. It consists of the following elements. The first is the All-Photonics Network (APN), which uses photonics-electronics convergence technology to provide significantly higher bandwidth and lower latency to the network. The second is Digital Twin Computing (DTC) for reproducing the real world in digital space on the basis of a large amount of sensing data from the real world. The third is Cognitive Foundation (CF) for integrated control from the transmission layer to application layer.

The APN, DTC, and CF require high processing power. In the IOWN era, the network functions implemented by dedicated network nodes, such as routers and mobile base stations, will be implemented as software. Therefore, the network nodes comprising the APN will be computers with high processing power such as high packet-processing rate and huge scheduling capacity. In DTC, computers must process a large amount of data collected from data sources, such as sensors and video cameras, with high definition and granularity. Therefore, they require much higher processing capacity than modern computer systems. CF needs to provide total control and management capabilities for the APN and DTC, such as proper control of computing resources and integrated control of computing resources and networks. To do this, it is necessary to aggregate and analyze a large number of network and computing requests and allocate appropriate bandwidth and wavelength as well as computing resources in a highly real-time manner. This requires quite high processing power



API: application programming interface
CTL: controller

Fig. 1. Conceptual diagram of IOWN.

that has not been available.

Achieving this high processing power with conventional computer architecture requires a large number of servers and consumes significant electric power. To make IOWN a reality, a computer with extremely high performance per unit power is indispensable to obtain the required high processing power without increasing the environmental load. NTT, through three laboratories, i.e., Software Innovation Center, Network Service Systems Laboratories, and Device Technology Laboratories, has begun developing a computer architecture called *disaggregated computing*, which uses photonics-electronics convergence technology to solve this problem.

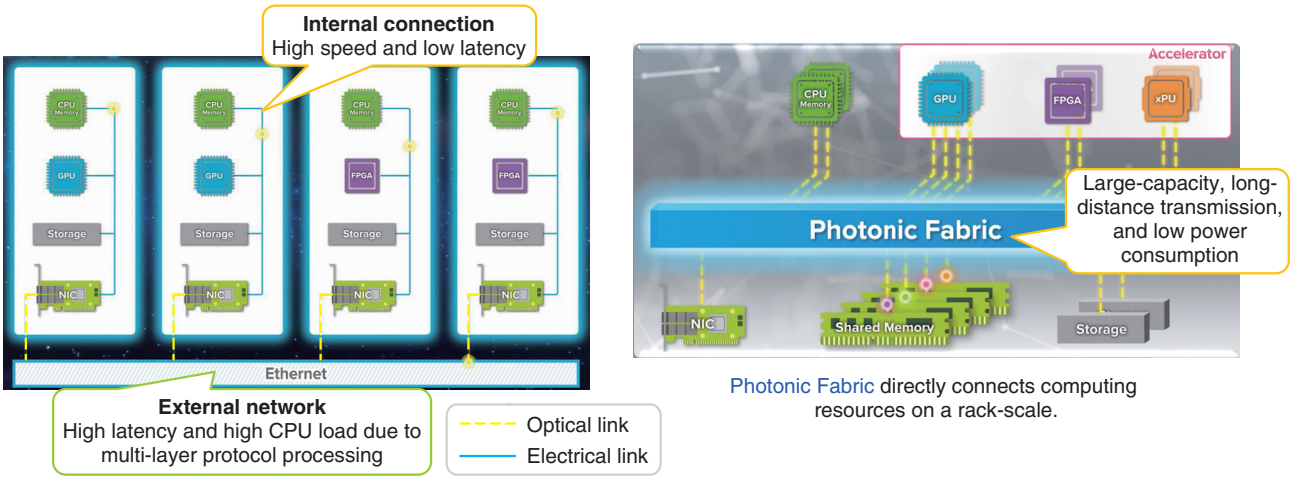
3. Details of disaggregated computing

Figure 2 shows the concept of disaggregated computing. This new architecture combines a physical configuration (hardware architecture), logical configuration (software architecture), and control scheme to maximize the high-speed, low-power consumption, and low-loss characteristics of photonics technologies and achieve overwhelmingly high performance compared with current computers. This architecture is a paradigm shift from the conventional server-oriented architecture of connecting a closed "computer" in a box via a network to the architecture of directly connecting resources such as central processing units (CPUs) and memory via optical interconnects and treating them as a computer on a rack-scale by using high-speed and long-reach photonics technologies.

The most important key technology of this architecture is the photonics-electronics convergence technology for enabling large-capacity, long-distance transmission, and low power consumption, which is impossible with electric technology alone.

In the conventional server-oriented architecture shown in Fig. 2(a), when data needs to be exchanged between servers, data must be transmitted and received by an external network. As network protocols have evolved to have a deep-layered stack to provide service functions such as reachability and path and session management, the overhead of protocol stack increases to communicate between servers.

In disaggregate computing, shown in Fig. 2(b), however, CPUs, graphics processing units (GPUs), field-programmable gate array (FPGAs), and other computing resources are connected via an interconnect (Photonic Fabric) using photonics-electronics convergence technology. This technology eliminates



(a) Conventional server-oriented architecture

(b) Disaggregated computing

Fig. 2. Concept of disaggregated computing.

protocol conversion for communication between resources, significantly reducing communication overhead, which is unavoidable in the current architecture. In contrast to the current configuration in which power control and adding hardware resources are done on a per-server basis, disaggregated computing enables power control and adding hardware resources to be done on a per-resource basis, making it possible to provide a more power-efficient and flexible computing environment.

The three key points of disaggregated computing are physical configuration, logical configuration, and function-placement control. The following describes each point in detail.

3.1 Point 1: Physical configuration

Figure 3 outlines the physical configuration of disaggregated computing. For high-speed electrical signals with speeds over 100 Gbit/s per lane, signal attenuation in the transmission path is a critical issue because of the physical principle that the higher the frequency of an electrical signal, the greater the attenuation in the transmission path. Such a high-speed signal exceeding 100 Gbit/s requires a high-power driver circuit and complex circuit that compensates for the signal waveforms degraded by attenuation. Both consume a huge amount of power. Even if these power-hungry circuits are used, only a few tens of centimeters can be transmitted. On the other hand, optical signals have the advantage of being able to transmit high-speed signals farther than electrical signals, with only 0.2 dB of power loss over 1 km of optical fiber transmission.

In disaggregated computing, compact photonics-electronics converged devices with high density, wide band, and low power consumption are mounted next to the large-scale integrated circuit (LSI) to immediately convert electrical signals from the LSI into optical signals. Therefore, the distance of the electrical signals can be kept the shortest between the LSI and adjacent photonics-electronics converged devices. By shortening the transmission distance of the high-speed electrical interface from the LSI, the power consumption of the high-speed interface on the LSI can be significantly reduced. NTT Device Technology Laboratories is studying and developing photonics-electronics converged devices for this application, and the details are described in an article in this issue [4].

Figure 4 shows a mock-up of a disaggregated computer. Cards with accelerators, CPUs, and other devices are connected by a backplane with optical wiring. Each card has compact high-density photonics-electronics converged devices mounted next to the LSI. High-speed multi-channel optical signals from the devices are connected to the backplane via optical traces on the card and optical backplane connector.

With such a configuration, it is possible to increase the scale of a computer from a box size to a rack-scale,

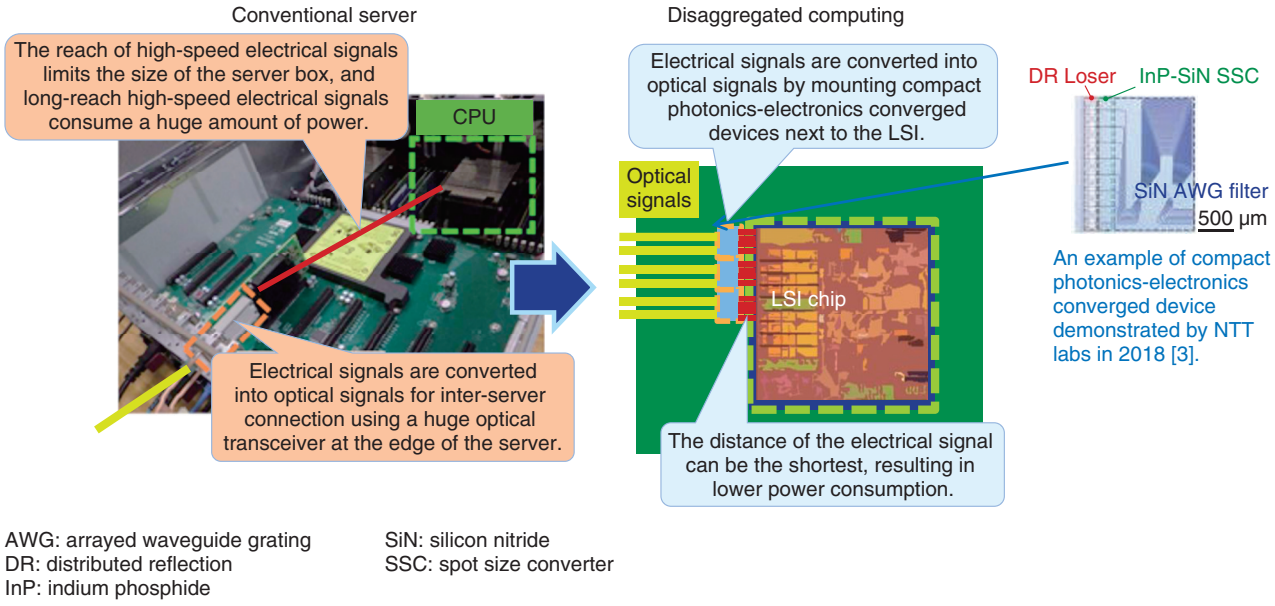


Fig. 3. Physical configuration of disaggregated computing.

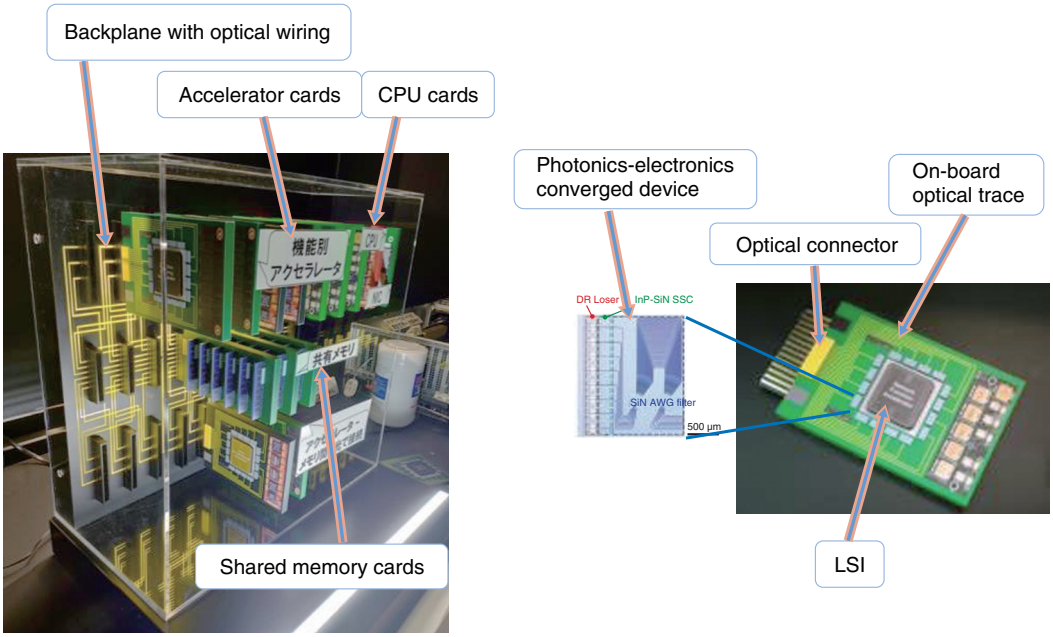


Fig. 4. Mock-up of the disaggregated computer.

exceeding the limit of the reach of the conventional electric signal. The processing capabilities of the computer can also be increased by adding cards on demand, providing a flexible and efficient system.

3.2 Point 2: Logical configuration

Figure 5 shows the logical configuration of disaggregated computing. Although a CPU has the advantage of executing all types of processing, its versatility makes it less power efficient than accelerators for

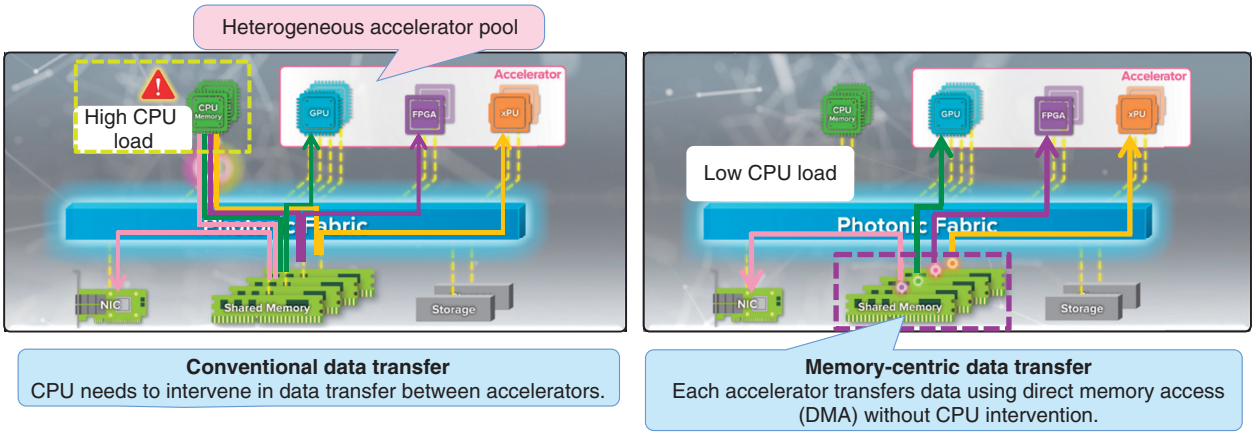


Fig. 5. Logical configuration of disaggregated computing.

specific workloads.

Therefore, with disaggregated computing, we aim to reduce CPU dependency by using accelerators for specific workloads. Accelerators are generally more power-efficient than CPUs when executing specific processes.

Since a disaggregated computer using optical interconnect can be made scalable compared with a conventional server, more accelerators can be efficiently aggregated into a computer. This enables a *heterogeneous accelerator pool* with several different accelerators that can offload the workload on the CPU, improving power efficiency.

However, even in this case, if the CPU needs to intervene in data transfer between accelerators, the CPU load will increase and the effect of offloading processing to accelerators will be lost. Therefore, NTT Software Innovation Center is promoting the study of greatly reducing CPU load by memory-centric data transfer without CPU intervention. This accelerator pooling and memory-centric data transfer between accelerators would significantly reduce CPU processing and improve power efficiency, which is described in an article in this issue [5].

3.3 Point 3: Function-placement control

To take full advantage of disaggregated computing with physical and logical configurations, it is important to control the arrangement of the software to make the most of this architecture.

For this purpose, NTT Network Service Systems Laboratories has proposed power-aware dynamic allocation-control technology for optimum utilization of computing resources, such as CPU and various accelerators, on the basis of software characteristics. As shown in **Fig. 6**, the software is divided into small functions, and devices such as accelerators and CPUs used by each function are dynamically selected by the power monitor & controller to minimize power consumption. It also uses a normally off device to provide event-driven control that turns on only when necessary. Details are described in an article in this issue [6].

4. Future plan

NTT laboratories are developing disaggregated computing on the basis of the innovative technologies described above. We will prototype and evaluate trial machines in combination with typical applications, such as image inference, and demonstrate disaggregated computing. In the long term, we will consider the introduction of photonics-electronics convergence technology into LSI chips, the latest research results on optical processing devices, and the development of more advanced architectures.

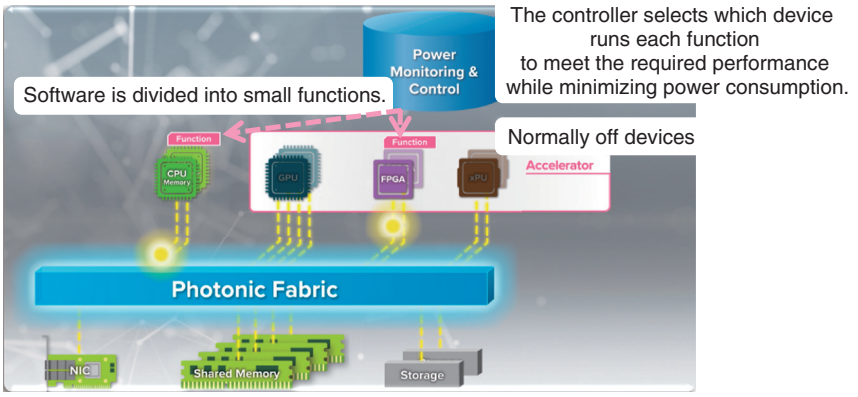


Fig. 6. Function-placement control of disaggregated computing.

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Photonics-electronics Convergence Technologies for Disaggregated Computing

Takeshi Sakamoto, Norio Sato, and Toru Segawa

Abstract

NTT is developing photonics-electronics convergence technologies to implement disaggregated computing. In this article, we describe the concept of photonics-electronics convergence technology, explain the effectiveness of introducing optical technologies into disaggregated computing, and introduce low-power-consumption devices under development.

Keywords: IOWN (Innovative Optical and Wireless Network), disaggregated computing, photonics-electronics convergence technology

1. Photonics-electronics convergence technologies supporting IOWN computing

As explained in the Feature Article "Disaggregated Computing, the Basis of IOWN" [1] in this issue, to make the Innovative Optical and Wireless Network (IOWN) a reality, it is necessary to develop computers that can efficiently process a large amount of data, which is incomparable with the past. Photonics-electronics convergence technologies are key to supporting computers that efficiently process large amounts of data.

The roadmap for photonics-electronics converged devices is shown in **Fig. 1** [2]. STEP 1 involves placing a compact optical module using silicon photonics technology around a central large-scale integrated circuit (LSI). STEP 2 involves placing optical transmission devices, such as semiconductor lasers and photodiodes, in the immediate vicinity of the LSI. STEP 3 involves connecting the LSI chip by optical wiring; as the generation progresses, the size and distance will continue to decrease. In STEP 1, development started targeting communication that connects computers, but as STEP 2 and STEP 3 evolve, the application area will shift to the in-device/in-board interconnect, and it is thought that the introduction of photonics into computers will progress (**Fig. 2**).

A rack-scale computer connection that is intended for a disaggregated computer requires a transmission distance exceeding several meters. This will be difficult to achieve by electrical connection because of the explosive increase in power due to the increase in speed and distance. The high-speed, high-density, low-power-consumption photonics-electronics converged devices in STEPs 2 and 3 convert electrical signals to optical signals in the vicinity of LSIs, enabling computers with high processing performance to be developed with lower power consumption without being bound by the limitations of electrical transmission.

This article describes the photonics-electronics convergence technologies for achieving low power consumption of disaggregated computers.

2. Need for an optical interconnect

This article explains the necessity of using photonics instead of electronics for the connection between boards (printed circuit boards) in a rack and the connection between LSIs on a board using the interconnect model. **Figure 3(a)** is an electrical model in which an LSI is mounted on a board and a high-speed signal converted from the clock frequency of the LSI

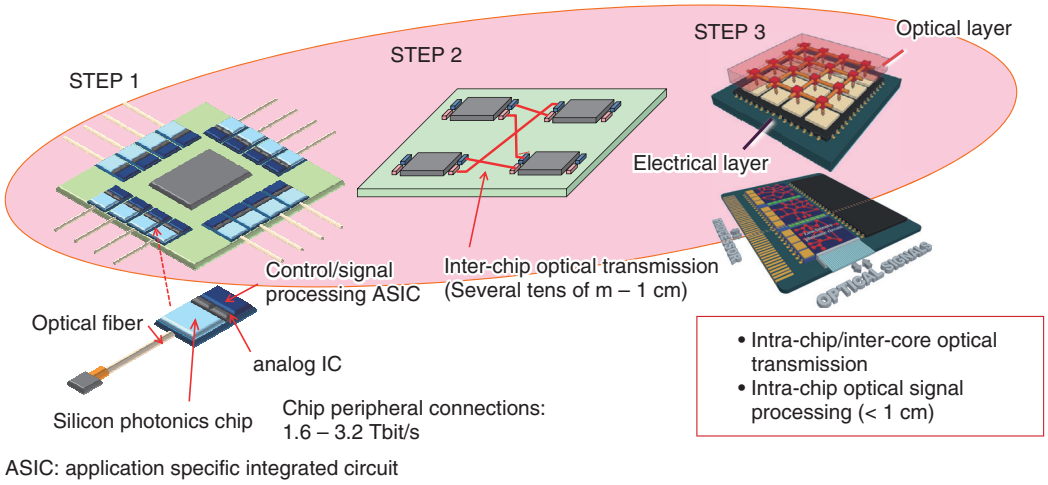


Fig. 1. Roadmap of photonics-electronics converged devices.

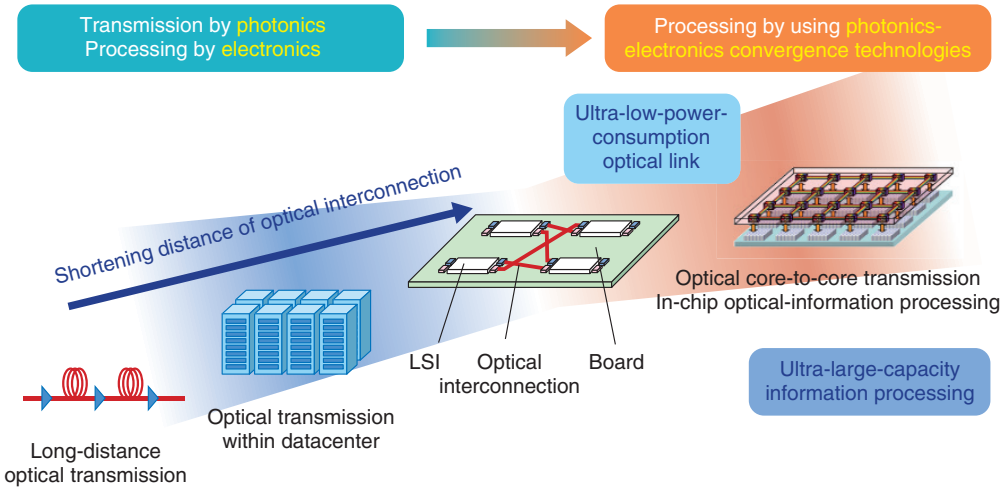


Fig. 2. Changes in application areas of photonics-electronics convergence technologies.

is connected to a transmitter on the way through the electrical wiring on the board. It is then received by a receiver formed on the board via a coaxial cable and sent to the LSI. In this case, assume that the length of the cable between the boards is L1 (m) and the wiring length on one board is L2 (m). **Figure 3(b)** shows the case in which an electrical-to-optical converter is placed after the transmitter to generate an optical signal and an optical fiber is used instead of a coaxial cable. In **Fig. 3(c)**, the transmitter and electrical-to-optical converter are integrated in the same package near the LSI. This configuration is called co-packaged optics (CPO) and corresponds to Figs. 1 and 2.

The loss values per unit length when high-speed signals propagate through boards, coaxial cables, and optical fibers are listed in **Table 1**. For 25-Gbit/s signals (refer to product values), the propagation loss of boards and coaxial cables is larger than that of optical fibers. For example, 3 dB/m for a coaxial cable means that the signal will be –3 dB, or half as large, during 1 m of propagation. Since it is difficult to measure a signal of 100 Gbit/s, an extrapolated value is shown. Various multilevel technologies based on a signal of about 25 Gbit/s (12.5 GHz) per channel are currently used, but the speed limit of CMOS (complementary metal-oxide semiconductor) technology will probably

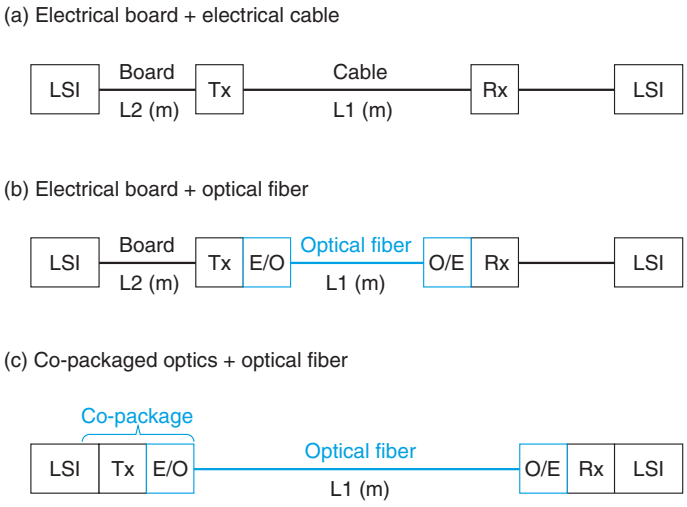


Fig. 3. Interconnect model.

be about 100 Gbit/s in the future. The higher the signal speed, the greater the loss in electrical signal transmission.

Figure 4 shows the results of estimating the relationship between power consumption and distance. The vertical axis in Fig. 4(a) shows the power consumption (mW) divided by the transmission capacity (Gbit/s) (i.e., mW/Gbit/s = pJ/bit) as an index, and the smaller the value, the better the efficiency. The horizontal axis is the length L1 (m) between boards. The calculation result is shown referring to the pluggable transceiver of 25 Gbit/s × 4 channels currently on the market. Comparing the cases in which the electrical cable is used and in which the optical fiber is used, the area where the electrical cable is advantageous and the area where the optical fiber is advantageous are divided at the boundary of 5 m. However, there is a lower limit (red circle) even in the case of the electrical cable. Figure 4(b) shows the relationship between the wiring length L2 (m) on the board and power consumption. This is determined by the power consumption required to transmit L2 = 0.3 m in the curve of 25 Gbit/s. Therefore, if CPO that makes L2 as small as possible are used, efficiency can be further improved, as shown with the sky-blue line in Fig. 4(a).

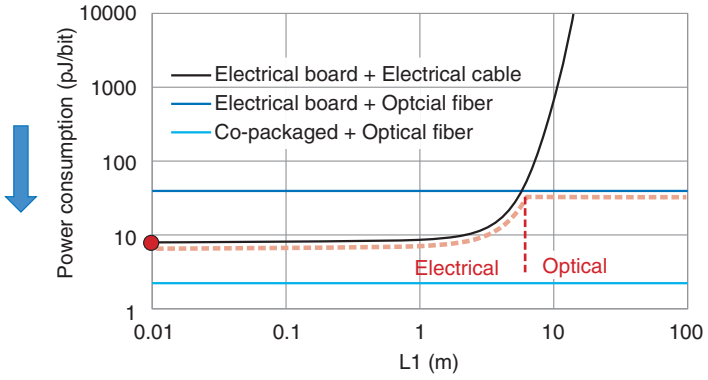
Next, consider the results assuming a transmission capacity of 100 Gbit/s, which will increase transmission speed in the future. As shown with the dotted line at 100 Gbit/s in Fig. 4(b), it is clear that the loss on the board becomes an order of magnitude larger, making the board unusable. Figure 4(c) shows the same estimate as 25 Gbit/s. In the future, power consumption can be reduced as much as possible by opto-electrical conversion in the vicinity of the LSI. When the speed is 100 Gbit/s compared with 25 Gbit/s, the frequency becomes 4 times higher, and the power consumption also increases. There is a need for photonics-electronics converged devices that consume less power while increasing speed.

Table 1. Propagation loss.

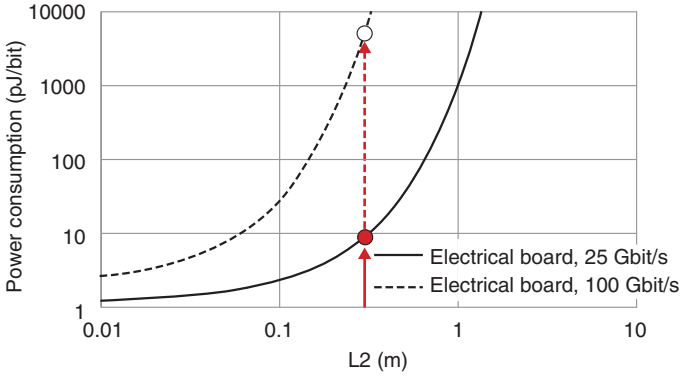
Loss (dB/m)		Transmission capacity	
		25 Gbit/s	100 Gbit/s
Electrical	Board	28	113 (extrapolation)
	Cable	3	9 (extrapolation)
Optical	Optical fiber	0.0003	0.0003

3. Products and research and development (R&D) trends related to interconnection

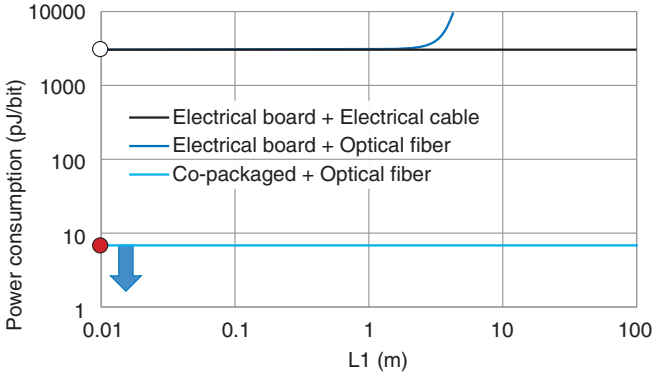
It was shown in the previous section that the applicable areas of photonics and electronics change



(a) L1 dependence (25 Gbit/s)



(b) L2 dependence



(c) L1 dependence (100 Gbit/s)

Fig. 4. Estimated power consumption efficiency. (a) L1 dependence (25 Gbit/s), (b) L2 dependence, and (c) L1 dependence (100 Gbit/s).

depending on the signal-transmission distance and speed by using a model. In this model, the case of single channel was explained, but multiple channels are bundled from the side of LSI and used. The higher the shoreline density (Gbit/s/mm), which is the transmission capacity (Gbit/s) per unit side length (mm) of the LSI, the higher the performance. In addition, the lower the power consumption per unit

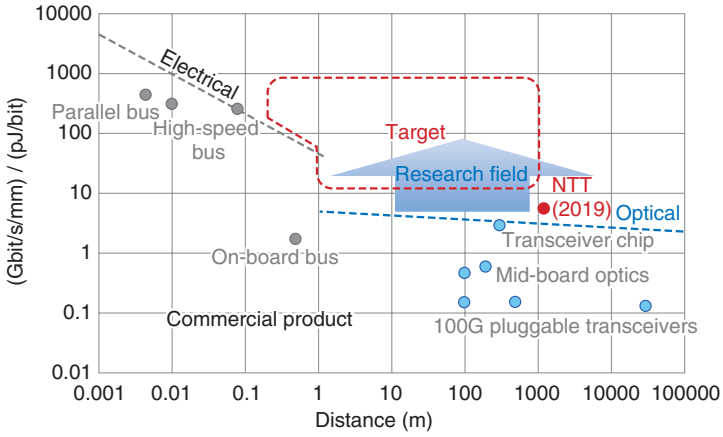
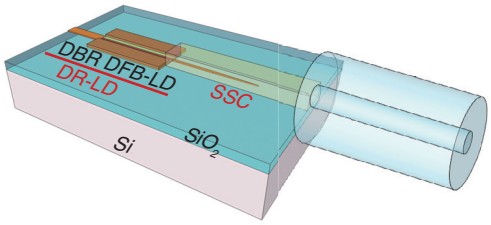


Fig. 5. Products and R&D trends related to interconnection.

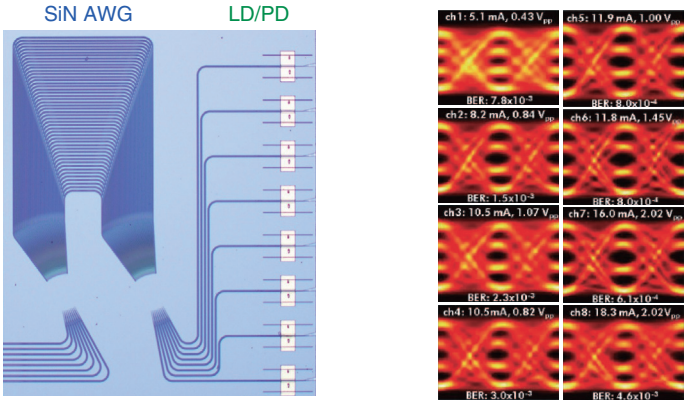
transmission capacity (pJ/bit), the higher the performance. Therefore, the value obtained by dividing the former by the latter, that is, high density/low power consumption = (Gbit/s/mm) / (pJ/bit), is used as the figure of merit. This figure of merit is shown on the vertical axis and distance (m) is shown on the horizontal axis in **Fig. 5**. When the values of commercial products for interconnection are plotted, although optical interconnection is applied over long distances, the figure of merit is about two orders of magnitude lower than that of electrical interconnection. To improve this figure of merit, low-power-consumption and high-density optical transceivers have been proposed by several R&D institutes. Optical technology, which can be used over a long distance of about 100 m, is expected to be applied to an area of about 10 cm, replacing the electrical area on the board with light. With disaggregated computing, data communication between LSIs and memories, which are limited by the size of physical servers, will be expanded to rack-to-rack scale (several tens of meters). In addition, when higher signal speeds are required, degradation of the figure of merit is predicted for electrical interconnection, so the target is to achieve a range of several centimeters to several tens of meters with a figure of merit equivalent to that of electrical interconnection using optical interconnection.

4. R&D on low-power, high-density devices at NTT

NTT is researching and developing low-power, high-density optical transmitters and receivers for the aforementioned target areas. The levels reached thus far (transmitter chip) are plotted in Fig. 5 [3]. Among optical transmitters and receivers, semiconductor lasers that convert electrical signals into optical signals are key optical devices. Thin film (membrane) lasers made by NTT are shown in **Fig. 6**. Vertical cavity surface emitting lasers (VCSELs) are currently the most commonly used semiconductor lasers for short-range optical communications such as board-to-board transmission. Although they have features of low power consumption and low cost, they are not suitable for wavelength division multiplexing technology because of their structure. To increase the communication capacity, high-density integration of single-mode lasers and a wavelength multiplexer is required. Against this background, NTT is developing a membrane directly modulated laser fabricated on a silicon (Si) substrate as a light source for short-range optical interconnects. By fabricating the laser on the Si substrate, the technology of Si photonics, which can produce optical devices such as wavelength multiplexers and photodiodes in high density and at low cost can be applied. By fabricating lasers on the silicon dioxide (SiO_2) layer with low refractive index, it is possible to reduce the size and power consumption of lasers by the high interaction between light and injected carriers. We have confirmed 25.8-Gbit/s non-return-to-zero direct modulation operation with energy consumption of 200 fJ/bit, which is comparable to VCSELs [4]. We also demonstrated 8 × 56-Gbit/s PAM-4 (four-level pulse amplitude modulation) operation with integration of an eight-channel directly modulated membrane-laser array and silicon nitride (SiN) arrayed waveguide grating (AWG) multiplexer on Si [5]. We are also



Membrane laser on Si substrate



Device photo　　Output signal waveform

Membrane laser integrated with wavelength multiplexer

DBR: distributed Bragg reflector
DFB: distributed feedback
DR: distributed reflection
LD: laser diodes
PD: photodiode
SSC: spot size converter

Fig. 6. NTT research example.

developing a laser using photonic crystals to achieve further low power consumption and size reduction [6].

5. Future development

As the signal speed and transmission capacity increase, the portion of electrical interconnection is replaced with optical interconnection, and light flows from the rack to the board and even into the board. Therefore, each computer that was previously confined within a physical server becomes a single computer connected at the rack scale. To support this paradigm shift with photonics-electronics convergence technology, we will advance R&D step by step. For photonics-electronics converged devices to be used from communications to information processing, further reductions in power consumption and cost as well as higher density are required. We will attempt to achieve the world of IOWN by applying such devices to future versions of disaggregated computing.

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Memory-centric Architecture for Disaggregated Computers

Teruaki Ishizaki and Yoshiro Yamabe

Abstract

At first glance, most of the technical components of a disaggregated computer seem to be hardware. However, simply using current software cannot enable efficient computing even if each hardware resource is connected directly with optical fibers. This article introduces the problems of current software that has evolved on the premise of high-speed central processing units and describes memory-centric architecture as a new data-exchange model for a disaggregated computer.

Keywords: disaggregated computer, memory-centric architecture, shared memory

1. Memory-centric architecture

Central processing unit (CPU) performance has evolved rapidly, as Moore's Law states that semiconductor integration will double every 18 months. Compared with this CPU evolution, memory and storage networks have evolved slowly. Therefore, most current software is designed on the premise of high-performance CPUs and other low-speed devices and the policy of shortening the processing time of other devices by conducting as many calculations on the CPU as possible.

When executing storage input/output (I/O), for example, the CPU efficiently adjusts the unit size of the I/O and request amount for the I/O target data stored in the memory. For processing that requires multiple accelerators, the software on the CPU controls the accelerators. Such a processing model, in which the CPU intervenes in processing, is called a CPU-centric computing model (**Fig. 1(a)**).

As a general software design, the CPU is designed to mediate processing. However, the growth of CPU core performance has slowed, which is said to be the limit of Moore's Law. Non-volatile memory, which is a high-speed storage, and accelerators, such as field-programmable gate arrays (FPGAs) and graphics processing units (GPUs), are rapidly evolving. A new software-processing model for improving the performance of various accelerators is also becoming more important.

Therefore, we are investigating a memory-centric architecture that enables efficient cooperation between various accelerators via the main memory. This architecture focuses on the main memory where an accelerator starts processing, enabling efficient data exchange via the main memory when accelerators are linked.

Memory-centric architecture is a data-exchange model in which the sender accelerator inputs data into the main memory (shared memory) and the receiver accelerator autonomously acquires and calculates the data. Taking the example of receiving data from another node with a network interface card (NIC) and processing it with an FPGA, in the CPU-centric computing model, the CPU controls the reception of the NIC and the execution of processing to the FPGA. However, memory-centric architecture requires only two minimum processes, NIC network-reception processing and FPGA-arithmetic processing, so CPU resource consumption and processing-time reduction to mediate the processing can be expected (**Fig. 1(b)**).

When multiple accelerators execute parallel processing using the data input to the memory, the sender accelerator only needs to be placed once in the shared memory area, which is a more efficient processing model (Fig. 1(b)).

A concept close to memory-centric architecture is Hewlett Packard Enterprise (HPE)'s Memory Driven

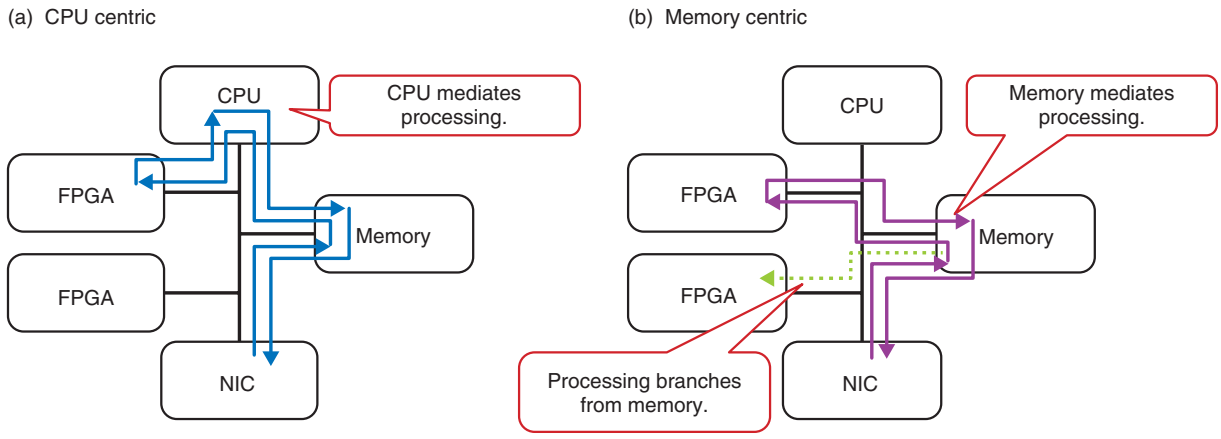

Fig. 1. Comparison of processing flow.

Computing (MDC) [1]. MDC is a concept model based on hardware architecture, such as a configuration in which a large memory pool is placed in the center of all processors. Memory-centric architecture, on the other hand, focuses on data control by software for exchanging data between accelerators via memory.

2. Evaluation on the effectiveness of memory-centric architecture

We evaluated the effectiveness of memory-centric architecture by using Sparkle [2, 3], which is an extension of Apache Spark (open source software for distributed data processing), as current software that is close to the concept of efficient data exchange via shared memory.

Apache Spark consists of a map phase that executes data processing in each worker process, shuffle phase that distributes the processing results executed in the worker process to the required processes, and reduce phase that executes operations on the basis of the results collected from each worker process. The shuffle phase is a process for exchanging a large amount of data by network communication using the TCP/IP (Transmission Control Protocol/Internet Protocol) between worker processes distributed over multiple nodes. Therefore, the shuffle phase's cost is very high in terms of CPU-processing delay related to network communication and CPU resource consumption. Sparkle is an extension that enables shuffle processing via shared memory for solving this problem.

Sparkle is software developed by HPE for MDC and is open source. However, its further development was suspended in 2016 when our evaluation study started, so we had to make some bug fixes to evaluate it [4].

Figure 2 is a comparison of Apache Spark (Fig. 2(a)) and Sparkle (Fig. 2(b)) data-exchange models assuming that multiple worker processes are running on the same server. Since connections are created between processes that exchange data, a large number of connections will be created due to the increase in worker processes as the processing scale increases. The process on the receiving side can refer to the data by receiving data through the network. However, to carry out network processing, it is necessary to execute data operations for transfer (protocol stack processing, memory copy to kernel space, etc.) on the CPU on both the transmitting and receiving sides. Therefore, this process increases delay. Since Sparkle can be referenced by other processes by arranging the data on the shared memory by the sending process, it is possible for the receiving process to acquire the data by referring to the memory area required. In other words, each process simply places the calculation result in the shared memory, and all processes can refer to the data without the CPU executing data operations for data transfer only, enabling efficient transmission and reception.

Graphs of Apache Spark and Sparkle performance test results are shown in **Figs. 3** and **4**. Figure 3 shows the performance comparison results of five basic processes including shuffle processing. The range of performance improvement differed since the ratio of shuffle processing to the entire processing differed depending on the processing. In particular, Sparkle

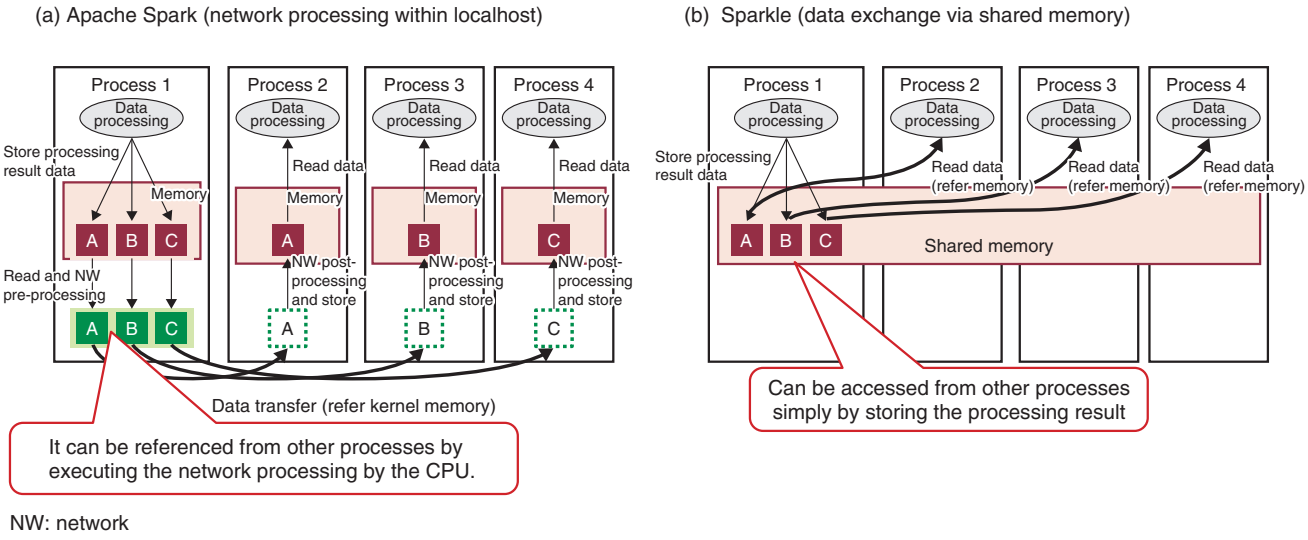

Fig. 2. Difference in data-exchange models.

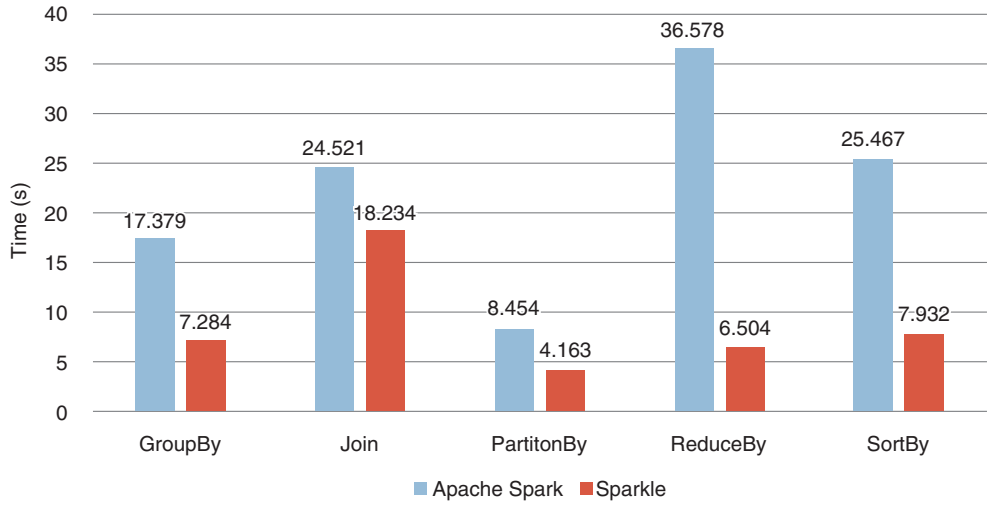

Fig. 3. Comparison of micro-benchmark result.

was about 6 times faster than Apache Spark in the case of ReduceBy, resulting in a significant performance improvement. Figure 4 shows the results of comparing the streaming processing performance using Spark Streaming. In this measurement, Sparkle had about twice the performance improvement compared with Apache Spark, and is expected to be effective for processing with strict delay requirements.

It was reconfirmed that the construction of a data-exchange model using shared memory enables efficient data exchange and reduction in delay, but there are issues in its construction. One of the biggest issues is the management of shared memory. It is common for the same file to be mapped by multiple processes when using shared memory, and it is necessary to use general C language pointer access to access the shared memory area. Although this can be described in general C language notation, memory management, such as access control of the shared memory area between multiple processes, free area management, and allocation, is not supported. Therefore, each application programmer needs to implement

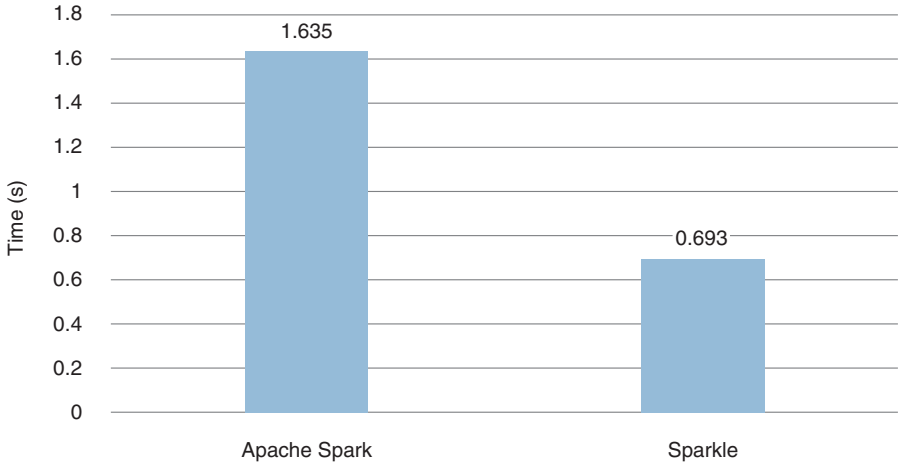

Fig. 4. Comparison of macro-benchmark using Spark Streaming.

their own memory management function to prevent data overwriting and double allocation of the memory area. The shared memory can be also used within a single server. To execute distributed processing across multiple servers, it is necessary to expand the function to enable such processing.

Research on software that does not impair the low latency of shared memory and that programmers can easily benefit from has become an important research subject for achieving memory centricity.

3. Conclusion

From the evaluation results of Sparkle, the effectiveness of using a data-exchange model via shared memory for a CPU was confirmed. As a study on memory-centric architecture, we will consider expanding this data-exchange model via shared memory to other accelerators such as FPGAs and study as a core technology that connects various hardware processes. Memory-centric architecture is positioned as an elemental technology required for disaggregated computers that support IOWN (Innovative Optical and Wireless Network) and is positioned as a software technology for using computer resources independently rather than on a server-chassis basis. By connecting and using accelerators without using a CPU through software control, we aim to reduce delay and CPU consumption.

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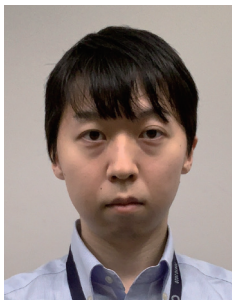

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Power-aware Dynamic Allocation-control Technology for Maximizing Power Efficiency in a Photonic Disaggregated Computer

Masashi Kaneko

Abstract

A photonic disaggregated computer developed as a computing platform of NTT's Innovative Optical and Wireless Network (IOWN) will consist of a variety of computing devices (energy-conserving central processing units, accelerators, etc.) distributed over a wide area. This article introduces power-aware dynamic allocation-control technology for maximizing power efficiency in a photonic disaggregated computer.

Keywords: energy conservation, disaggregation, heterogeneous computing

1. Power-related problems in server systems in the IOWN era

Internet Protocol traffic has been growing exponentially with expectations that it will reach 4000 times its current level by 2050. At the same time, the speed of improvements in central processing unit (CPU) performance on servers that process that traffic is slowing down. A trial calculation showed that the power needed for datacenter operation will likewise increase by 4000 times by 2050 given the power efficiency of today's server hardware. Improving the energy conservation and power efficiency of servers is therefore critical for future network operation.

With the Innovative Optical and Wireless Network (IOWN), our aim is to develop a photonic disaggregated computer as a new network-wide computer that can execute high-speed and efficient processing in a network via computing devices connected over the All-Photonics Network (APN), one of the main components of IOWN. A photonic disaggregated computer will introduce new devices and processing methods such as photonics-electronics convergence devices and memory-centric computing. Therefore, it is expected to achieve a level of power performance surpassing the limits of current server hardware and solve power-related problems into the future.

2. Photonic disaggregated computer and power-aware dynamic allocation-control technology

Distributed heterogeneous computing can be achieved through the connection of diverse devices such as CPUs and accelerators (graphics processing units (GPUs), field-programmable gate arrays (FPGAs), etc.) as computing devices that make up a photonic disaggregated computer. When operating virtual network functions (VNFs) as a group of virtual functions making up a network on such a computing platform, a control mechanism is needed to allocate the software components configuring a VNF (in a conventional VNF, this would be virtual machines (VMs)) to each computing device. In a conventional VNF, a VM requiring an accelerator would have to be located in server hardware physically equipped with an accelerator. It is also common in standard VMs to use an accelerator in an exclusive

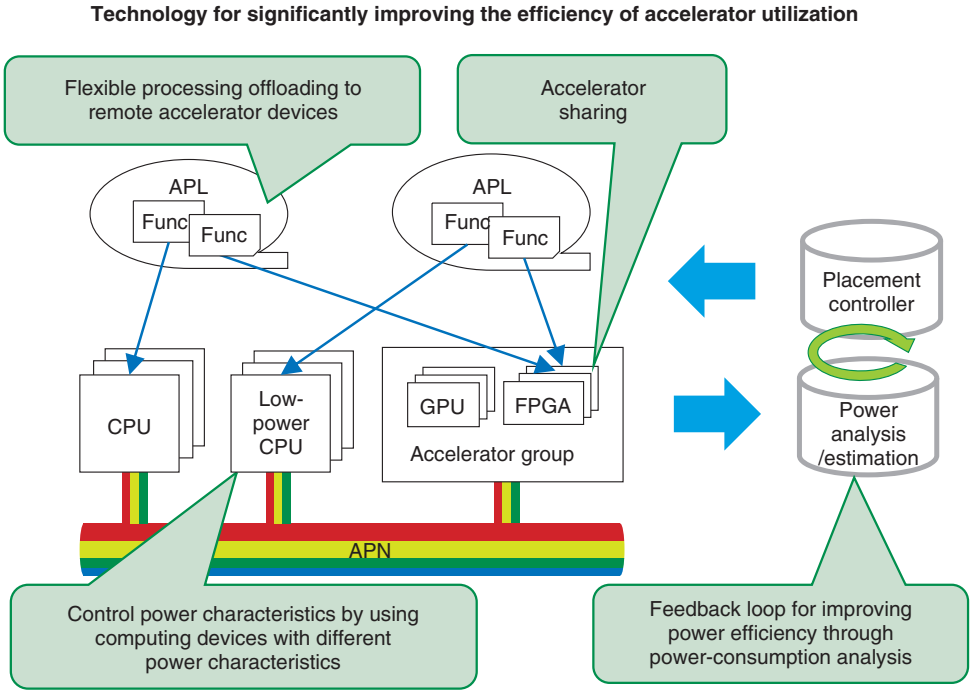

Fig. 1. Power-aware dynamic allocation-control technology.

manner in units of devices (GPU board, FPGA board, etc.). This means that the hardware resources of an accelerator cannot be effectively used on a server deploying an application having a low ratio of processing offloaded to the accelerator. In a photonic disaggregated computer, computing devices, such as CPUs and accelerators, are connected over optical paths, enabling high-speed, low-latency interaction between physically separated devices and an easing of configuration constraints caused by the physical form of a conventional server (e.g., the number of extension boards that can be mounted in a rack-mount server). Assuming that N is the number of accelerators used by the VNF and M is the number of VNFs using the accelerator, if the conventional 1-to-N relationship between the VNF and accelerators can be made into a more flexible M-to-N relationship, it will become possible to allocate the processing of multiple VNFs to a single accelerator, thus maximizing the use of an accelerator's hardware resources.

The power-aware dynamic allocation-control technology being developed at NTT Network Service Systems Laboratories will contribute to a reduction in power consumption through software control of the server platform (**Fig. 1**). We are developing two key technologies toward this goal. The first is technology for significantly improving the efficiency of accelerator utilization to facilitate the sharing of accelerator devices and improve the availability rate of accelerators. This is accomplished by enabling the offloading of processing to accelerator devices distributed across the network and, in contrast to the conventional practice of exclusive access, by accepting parallel processing when software components running on multiple CPUs attempt to simultaneously access an accelerator. The second is green-energy-based server-platform technology to control power demand and make maximum use of power obtained from unstable renewable-energy power generation in an environment composed of diverse computing devices such as low-power CPUs and various types of accelerators. This will be achieved by analyzing power consumption in detail in units of devices and software components and reducing power by appropriately placing software components that can minimize power consumption and controlling energy conservation in

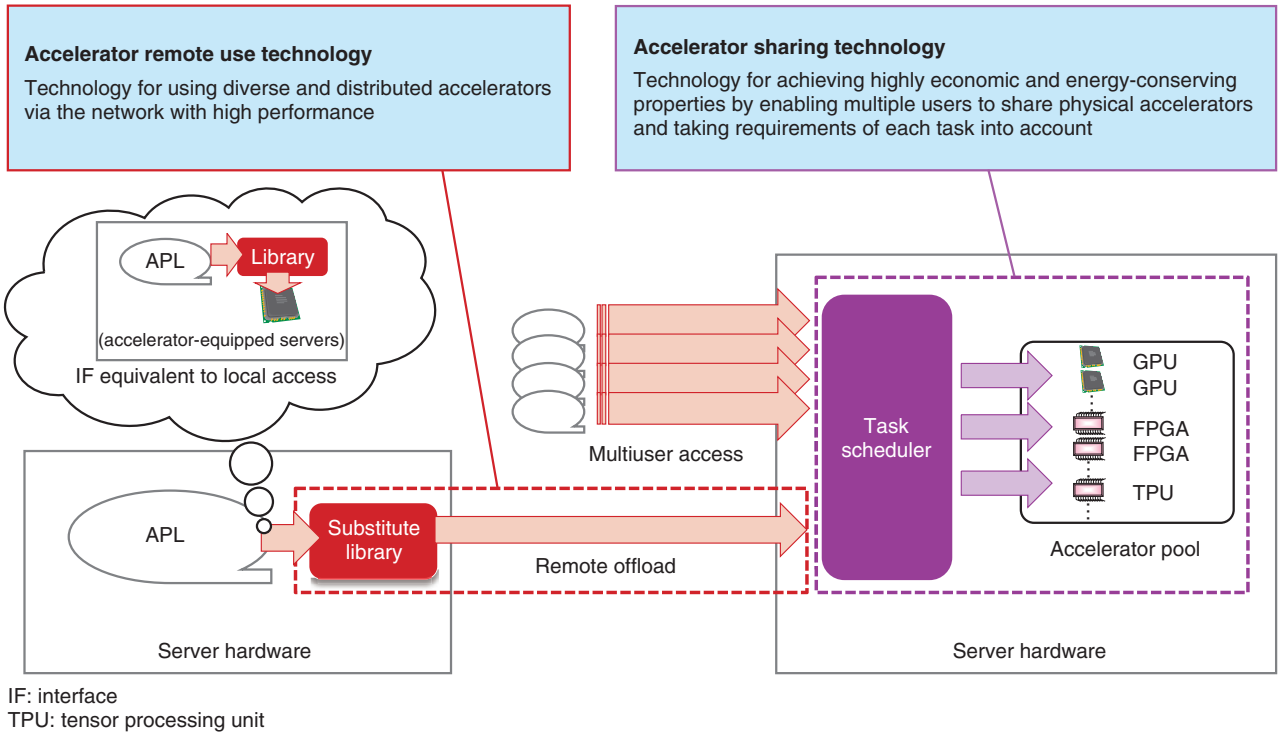

Fig. 2. Technology for significantly improving the efficiency of accelerator utilization.

individual devices. This could be done by adjusting power consumption on the server platform that takes into account the status of renewable-energy power generation in individual regions.

3. Technology for significantly improving the efficiency of accelerator utilization

The use of GPUs and FPGAs in addition to CPUs has been increasing in complex computational processing such as data analysis and machine learning. Accelerators, though usually weak in terms of general-purpose processing, can execute specialized processing more than 100 times more efficiently than CPUs. When using accelerators, it is a common practice to offload a part of a program running on a CPU to an accelerator via an application programming interface (API) such as OpenCL. However, such offloading cannot be done if an accelerator in idle state does not exist on the same server hardware as the CPU running the program.

We are developing a technology that significantly improves the efficiency of accelerator utilization. It does this in two ways. First, it enables high-speed, low-latency use of remote accelerators distributed over the network with location transparency and low overhead just as if they were locally placed without being tied to a conventional physical-connection configuration. Second, it enables multiple users to share these accelerators (**Fig. 2**). In the offloading of processing to remote accelerators, location transparency can be achieved and the portability of existing applications can be improved by incorporating a substitute library that provides an existing offloading API (e.g., OpenCL API) to the offloading source and by providing an interface equivalent to conventional local access to the application.

4. Green-energy-based server-platform technology

Current server hardware has been designed assuming a continuous and stable supply of power, so a datacenter accommodating many servers must be able to provide a large amount of power in a continuous and stable manner. There has been a move to use renewable energy in the power feed to datacenters, but since current servers require a continuous and stable supply of power, as described above, it is difficult to achieve long-term stable operation only on

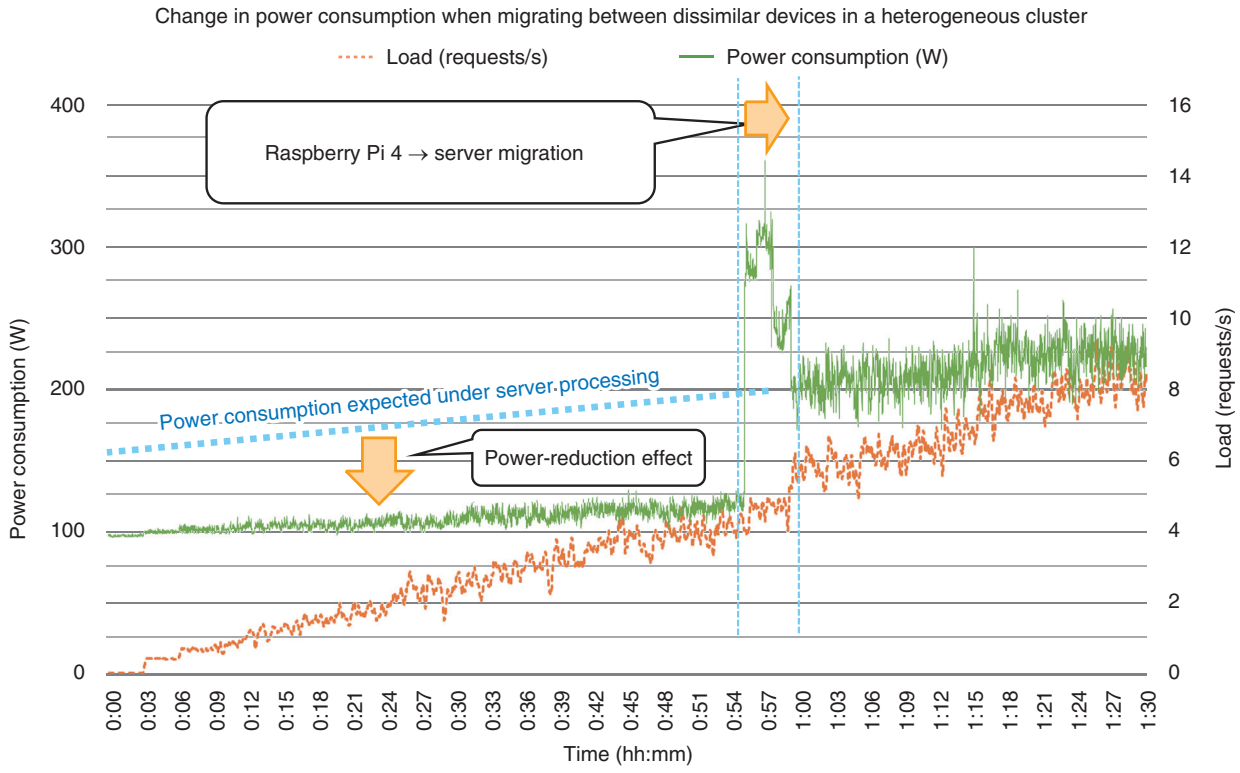

Fig. 3. Example of energy-conservation control in a heterogeneous cluster.

the basis of renewable energy in which the amount of power generated is unstable, as in the case of solar power generation. Green-energy-based server-platform technology controls power in units of computing devices and controls the placement of software components that make up the system by analyzing and estimating the power consumed by servers. This enables energy conservation over the entire software platform and operation control corresponding to the amount of power being supplied.

Standard server hardware in a low-load state still consumes about 60–70% of the power consumed in a high-load state. A system on a chip (SoC) installed in smartphones decreases as much power consumption in a low-load state as possible by controlling operation in accordance with power-supply conditions (battery storage), as in the smartphone "power-saving mode." This includes measures such as CPU power state control and frequency control tailored to the load and mounting of CPU cores particularly suitable for low-power operation. On a server platform, as well, if power demand can be adjusted by varying performance on the basis of the amount of supplied power, it should be possible to achieve a server platform that can use ever-fluctuating renewable energy in a non-wasteful manner. As an alternative approach, power efficiency could be improved by configuring a heterogeneous cluster of servers that combines multiple types of servers with different levels of power performance and dynamically selecting optimal servers in accordance with operating conditions.

To give an example, power improvements could be achieved at low loads by configuring a heterogeneous server cluster that combines standard server hardware and computing devices that, while having low maximum performance, excel in power performance such as the Raspberry Pi computer, selecting optimal servers in accordance with load conditions, and executing system migration dynamically. The graph in **Fig. 3** shows power consumption when configuring a Raspberry Pi cluster consisting of 15 Raspberry Pi 4 devices and one 1U (unit) rack-mount server and executing software-component migration on the basis of load. From these results, processing by the Raspberry Pi cluster in a low-load state (1U rack-mount server is OFF) can be achieved at a level of power, even lower than that of the server in idle state (about 150 W). Therefore, power efficiency can be improved

across a wide range of loads by combining multiple computing devices having different power characteristics and controlling the placement of software components making up the system on the basis of load.

5. Future developments

The power consumed by information technology services is growing and expected to become an increasingly serious problem. Going forward, we will continue to investigate power-aware dynamic allocation-control technology to solve this problem by efficiently controlling a photonic disaggregated computer. We will also promote technology development to contribute to the creation of a low-carbon society. To this end, we will pursue the use of renewable energy in combination with our quest for higher levels of power efficiency in addition to solving performance and cost issues.

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He received an M.E. from the University of Electro-Communications, Tokyo, in 2004. He joined NTT Network Service Systems Laboratories the same year and studied network server platform technologies including web-telecom service convergence, and a sharding method of telecom systems. From 2015 to 2017, he engaged in the development of commercial NFV/software-defined wide area network services at NTT Communications Corporation. He is currently studying photonic disaggregated computers.

Latest Activities in TM Forum

Shingo Horiuchi and Kenichi Tayama

Abstract

Since its establishment in 1988, TM Forum has been shifting from examining and standardizing telecommunication operations (i.e., carrier business support system and operations support system (BSS/OSS)) on the basis of the Telecommunications Management Network model to examining and standardizing next-generation operation-system frameworks/architectures for business-to-business-to-X (where X denotes any end user) services cooperating with other companies and industries. These activities are being carried out in areas of *autonomous networks* for automating network operations using artificial-intelligence technology and *customer experience management* for strengthening customer-oriented operations. The NTT Group is promoting its technical and business requirements to be reflected in the standardization process in the forum, as well as examining the architecture of BSS/OSS for digital transformation using the forum's documentation.

Keywords: TM Forum, autonomous network, customer experience management

1. What is TM Forum?

TM Forum [1] started as the Open Source Initiative/Network Management Forum in 1988 and is the largest international standardization organization in the telecom management field with more than 850 associated major carriers and vendors worldwide studying industry standards in the operations field to promote interoperability. The Open Digital Architecture (ODA) was proposed as an architecture of business support system and operations support system (BSS/OSS), and the framework to implement this architecture is defined as the Open Digital Framework (ODF). The forum also discusses categories set on the basis of business trends (projectivization), architecture, application programming interfaces (APIs), information models, and so on that are based on specific use cases and scenarios. Discussions have been held on projects such as the Autonomous Network Project, which aims at autonomous network operations, Customer Experience Management (customer-oriented operations) Project, which aims at improving customer satisfaction, and Digital Ecosystem Management Project, which aims at applications for smart cities (including Internet of Things), etc. Proof-of-concept (PoC) (Catalyst) programs are being carried out to demonstrate the feasibility of these standard documents in terms of implementation and applicability in new business fields, and about 40 teams (one team consists of five to ten carriers/vendors) participate annually. These PoCs are exhibited several times a year at TM Forum events (Digital Transformation World, etc.), where a number of carrier vendors demonstrate their new business models and technical capabilities that contribute to the forum's standardization activities (**Fig. 1**).

2. Trends in telecommunications business

Traditionally, telecommunications carriers have provided telephone and Internet services as lifelines, and their operations require sustainable connectivity and cost reduction. Accordingly, TM Forum has been studying business process and management information models to meet such requirements. However, new networks, such as fifth-generation mobile communication systems (5G), are increasingly providing network services not only to direct line users such as corporations and individuals but also for businesses involving different industries. Therefore, the main focus of TM Forum has been the architecture and interface (API) of an operation that uses the cooperation between business operators to respond to a business-to-business-to-X (B2B2X) business model

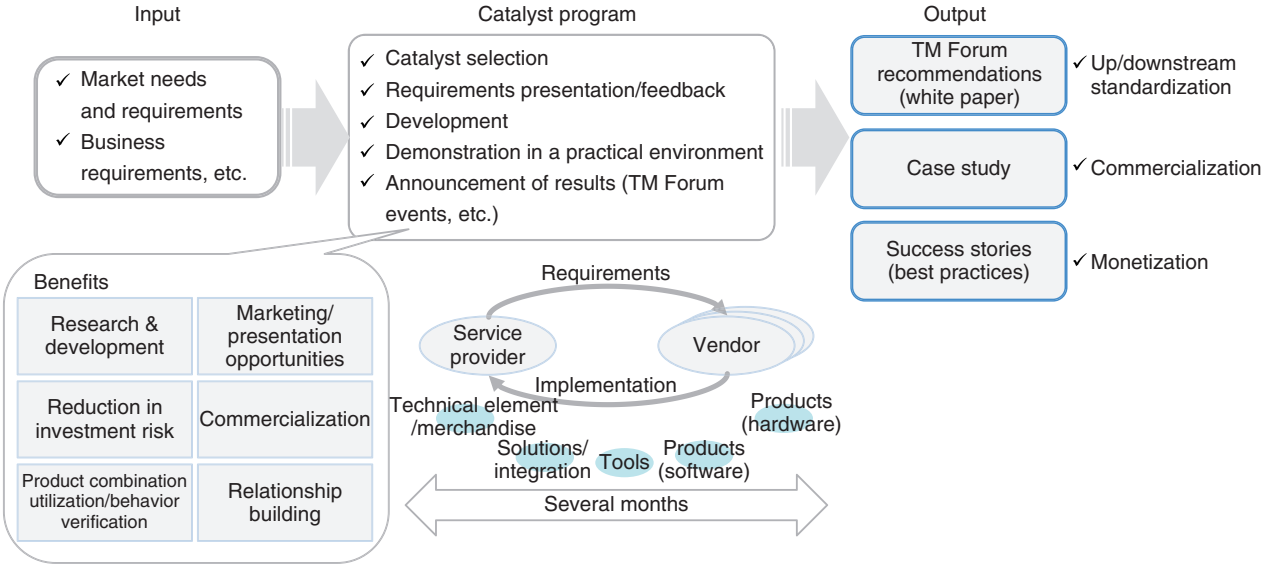


Fig. 1. PoC (Catalyst) positioning at TM Forum.

shifting from a conventional business-to-consumer (B2C) business model. One of the main features that sets TM Forum apart from other standardization organizations is the emphasis placed on discussions based on business models. To establish architecture, API, and an information model as standards, members of TM Forum discuss these requirements on the basis of business models. In the Catalyst program, carriers and vendors discuss new business models and demonstrate the effectiveness of assets (e.g., standard specifications) stipulated by the forum. The standardization elements necessary for new business requirements are also discussed.

3. Standardization trends

3.1 Operational architecture – ODF/ODA

TM Forum's Frameworx specifications inherited assets from the New Generation Operations Systems and Software (NGOSS) era, and the forum uses NGOSS documents on enhanced Telecom Operations Map (eTOM), Shared Information/Data model (SID), Telecom Application Map (TAM), Open API, metrics, and best practices to examine these assets. Since around 2018, these frameworks have been drastically changed and restructured as the ODF. The ODA of the system construction in the ODF is discussed on the basis of elements such as the B2B2X business model, customer orientation, and use of artificial intelligence (AI) while inheriting the Frameworx assets (**Fig. 2**).

In addition to a previous study, a study has begun on ODA-component accelerator (ODA-CA) implementation that accelerates the development of information technology solutions using the ODA. We are also undertaking a large-scale restructuring for using the ODA as a system framework for a wider range of businesses and improving the consistency between the ODA and existing Frameworx assets. On the basis of the concept of enterprise architecture (e.g., The Open Group Architecture Framework (TOGAF)), we are planning to divide ODA documents into business architecture, data architecture, functional architecture, components, and Open APIs and map existing assets such as eTOM, SID, and TAM as libraries.

3.2 API

Discussions held at TM Forum among various industries along with telecom operators and systems vendors support using APIs (Open API) to create business led by telecom operators and linked with other industries, and 71 companies have agreed on a manifest. There have been several discussions on API suites (a set of necessary APIs) for specific business and network technologies such as edge management component suite APIs, AI closed-loop management component suite APIs, and connectivity as a service component suite APIs.

3.2.1 Autonomous network considerations

TM Forum has been developing a closed-loop

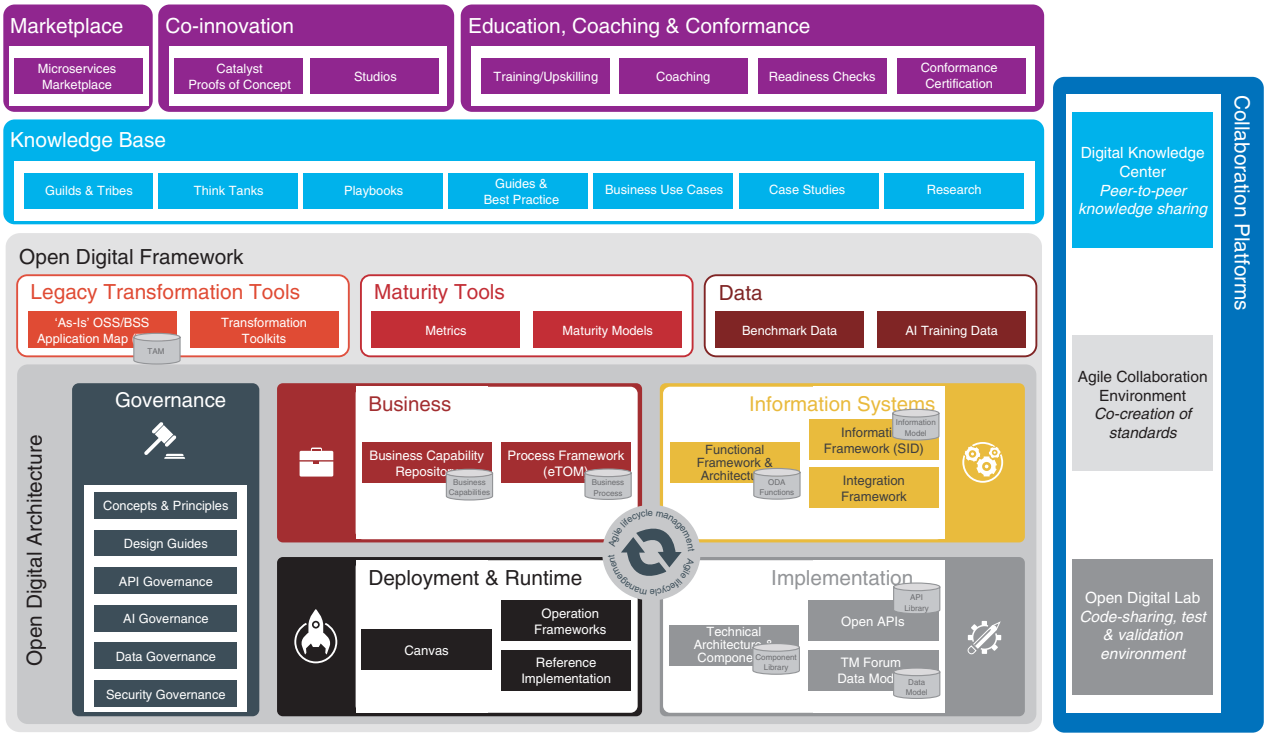


Fig. 2. TM Forum scope and ODF/ODA.

framework that automates managed operations through the collection, analysis, optimization, and execution of networks and other managed information. The Autonomous Network Project has been working on business models, architectures, and APIs to extend the closed-loop concept and automate business processes. This is an effort to achieve business automation by linking closed loops at the resource, service, and business layers of a network. In the Autonomous Network Project, the level of automation can be set, and each carrier can objectively determine the level of automation (**Fig. 3**).

While other standardization organizations, such as European Telecommunications Standards Institute (ETSI) Industry Specification Groups on Zero-touch network and Service Management (ZSM) [2], Experiential Networked Intelligence (ENI) [3], and Fifth Generation Fixed Network (F5G) [4], and open source organizations, such as Open Network Automation Platform (ONAP) [5], are also working on this type of framework for automation, TM Forum is leading a very collaborative effort among these organizations (**Fig. 4**).

Fiscal year 2020 saw advanced documentation of business requirements and architectures. In the architecture, the concept of an intent (relationship between upper-layer and lower-layer requirements) is being recognized as an element that links closed loops in each layer. Fiscal year 2021 will see advanced discussions on modeling this intent and making it an API.

The autonomous network abstracts the infrastructure and treats it as a network as a service (NaaS). In a NaaS, connectivity of services based on location, price, and service level agreement (SLA) is expressed as connectivity as a service (CaaS). Based on the abstraction of the infrastructure, the autonomous network has expanded its scope to include not only 5G networks but also legacy networks, and methods of automating operations using AI are being studied (**Fig. 5**).

3.2.2 Operations using AI

At TM Forum, there are four items to consider when using AI in operations to make them more effective:

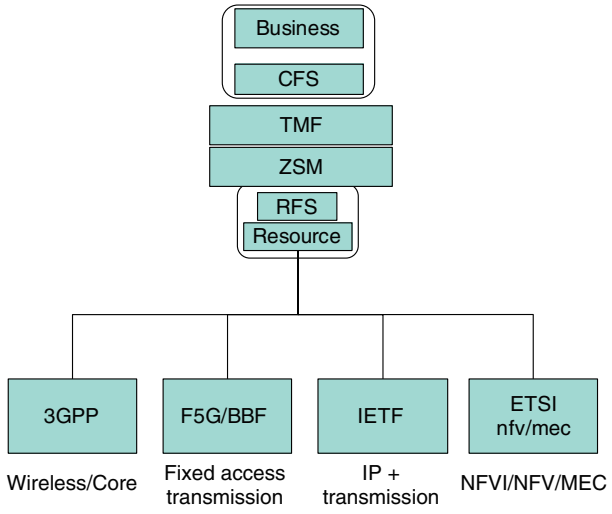
(1) Closed-loop AI automation: Exploring architecture that enables automation using AI for anomaly analysis. We are organizing expected use cases and logical architectures for anomaly detection and resolution.

(2) AI governance: Studying management and

Autonomous levels	L0: Manual Operation & Maintenance	L1: Assisted Operation & Maintenance	L2: Partial Autonomous Network	L3: Conditional Autonomous Network	L4: High Autonomous Network	L5: Full Autonomous Network
AN services (Zero X)	N/A	Individual element	Individual AN case	Select AN cases	Select AN services	Any AN service
Execution	P	P/S	S	S	S	S
Awareness	P	P	P/S	S	S	S
Analysis/Decision	P	P	P	P/S	S	S
Intent/Experience	P	P	P	P	P/S	S

Personnel (manual)
Systems (autonomous)
AN: autonomous network

Fig. 3. Autonomous network-level definitions.



BBF: Broadband Forum
CFS: Customer Facing Services
IETF: Internet Engineering Task Force
IP: Internet protocol
NFV: network functions virtualization
NFVI: network functions virtualization infrastructure
MEC: multi-access edge computing
RFS: Resource Facing Services
3GPP: 3rd Generation Partnership Project

Fig. 4. Relationship between study areas and other standards.

risk-reduction methods to widely deploy operations using AI. We are studying methods of managing operation life cycles using AI, taking into account business alignment and business design.

(3) AIOps[*1]: Studying AI-based operational process designs. We are focusing on operational processes and their governance using AI by analyzing the gap between traditional management processes of service operation on the

*1 AIOps: Automated operations with AI technologies.

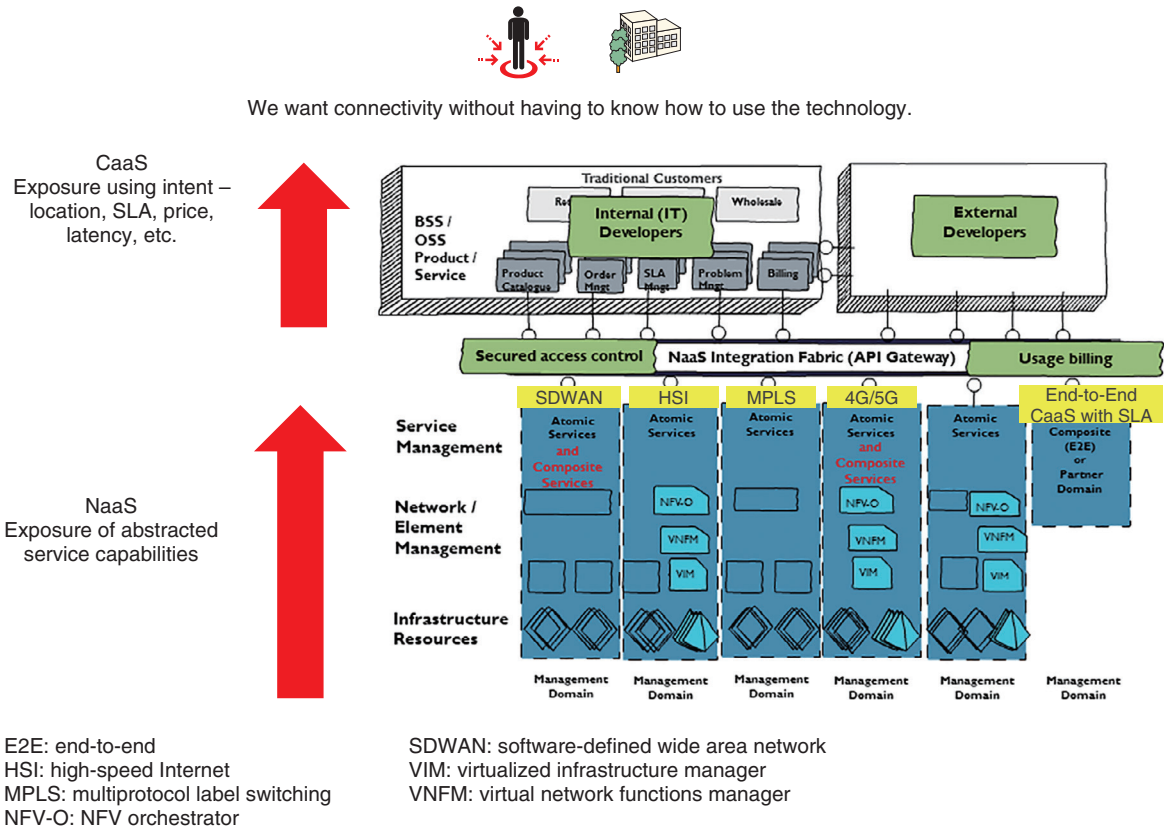


Fig. 5. Relationship between NaaS and CaaS.

basis of practices such as DevOps[*2] and Information Technology Infrastructure Library and the process based on AI and by providing AIOps service management as a framework based on the extracted requirements. This framework is under consideration.

(4) Data governance: Considering an ethical and secure framework. We are considering categorization of learning data for operations using AI and the right to share and use those data.

3.2.3 Customer-oriented operations

The key quality indicators specialized for services used by customers have been used for customer experience management, and how the service management process improves customer satisfaction has been examined. Considering that many customers use various services in combination, study on the life cycle of service use from the customer's viewpoint has progressed by taking into account situations in which customers change services according to changes in their lifestyles. Consideration of customer-oriented operations in 5G businesses and operations based on the intent of the customers' service requirements is a popular topic in TM Forum.

4. NTT Group activities

The NTT Group is using TM Forum to understand market trends and technologies for digital transformation, reflect operation technology developed by NTT laboratories in international standards (avoiding "Galápagosization"), create business models that combine market technologies with NTT's technology, and promote the commercialization of NTT Group packaged products. For example, NTT Access Network Service Systems Laboratories is working on modeling technology for network resource information (NOIM: Network Operation Injected Model) to be reflected in information model requirements for network management and developing related APIs for inter-business cooperation for resource information

*2 DevOps: The collaborative work between development and operation teams to achieve agile development based on the operator's requirements.

and internetworking, service, and business cooperation. NTT Group companies participate in the TM Forum Standardization Technical Committee before and after major meetings and events of TM Forum with the aim of integrating activities and operations within the NTT Group. The committee shares upstream and downstream information from each company and shares the trends and relationships of related standardization organizations with TM Forum. It has also established a support system to effectively encourage the upstream and downstream activities of each company.

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[2] ETSI ZSM, https://www.etsi.org/committee/zsm
[3] ETSI ENI, https://www.etsi.org/committee/eni
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[5] ONAP, https://www.onap.org/

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External Awards

Fellow
Winner: Seishi Takamura, NTT Media Intelligence Laboratories
Date: March 11, 2021
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE)

For his research and development on video coding and its dissemination.

Paper Award
Winners: Ryota Tanaka, Kyosuke Nishida, and Sen Yoshida, NTT Media Intelligence Laboratories
Date: March 18, 2021
Organization: The 27th Annual Meeting of the Association for Natural Language Processing (NLP2021)

For "VisualMRC: Machine Reading Comprehension on Document Images."
Published as: R. Tanaka, K. Nishida, and S. Yoshida, "VisualMRC: Machine Reading Comprehension on Document Images," NLP2021, A5-1, Fukuoka, Japan, Mar. 2021 (in Japanese).

Shigeo Tsujii Security Paper Award
Winners: Takuya Watanabe, Eitaro Shioji, Mitsuaki Akiyama, NTT Secure Platform Laboratories; Tatsuya Mori, Waseda University
Date: April 22, 2021
Organization: Japan Society of Security Management

For "Melting Pot of Origins: Compromising the Intermediary Web Services that Rehost Websites."
Published as: T. Watanabe, E. Shioji, M. Akiyama, and T. Mori, "Melting Pot of Origins: Compromising the Intermediary Web Services that Rehost Websites," The 26th Network and Distributed System Security Symposium (NDSS 2020), San Diego, CA, USA, Feb. 2020.

Best Paper Award
Winners: Tomoya Kageyama, NTT Network Innovation Laboratories; Osamu Muta, Kyushu University; Haris Gacanin, Nokia Bell Labs
Date: April 27, 2021
Organization: IEICE

For "Enhanced Selected Mapping for Impulsive Noise Blanking in Multi-carrier Power-line Communication Systems."
Published as: T. Kageyama, O. Muta, and H. Gacanin, "Enhanced Selected Mapping for Impulsive Noise Blanking in Multi-carrier Power-line Communication Systems," IEICE Trans. Commun., Vol. E102-B, No. 11, pp. 2174–2182, 2019.

ITU-AJ Accomplishment Award
Winner: Jun-ichi Kani, NTT Access Network Service Systems Laboratories
Date: May 17, 2021
Organization: The ITU Association of Japan (ITU-AJ)

For his leadership in standardization activities regarding optical access systems as a rapporteur at Study Group 15 in the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T), thus contributing to the acceleration and sophistication of optical access networks. He also facilitated discussion on optical access systems and promoted the formation of a technology roadmap in the Full Service Access Network initiative, contributing to speeding up the development of ITU-T recommendations.

Papers Published in Technical Journals and Conference Proceedings

Aging Estimation of an AC Adapter from Generated Electromagnetic Noise
F. Ishiyama and Y. Toriumi
The 20th IEEE International Symposium on Signal Processing and Information Technology (ISSPIT 2020), December 2020.

Capacitors are the parts of a power supply unit that deteriorate most easily. Among types of power supply unit, alternating current (AC) adapters are the ones for which it is not possible to check the leakage or bulging of capacitors, because they are sealed and invisible. Therefore, we focused on the electromagnetic noise which deteriorated AC adapters emit on the power line. We measured their noise and analyzed them with our own method of mode decomposition. It was found that the intensity of the noise is proportional to the internal resistance of the deteriorated capacitors measured in the hot condition.

Identification of Transcription Factors and the Regulatory Genes Involved in Triacylglycerol Accumulation in the Unicellular Red Alga *Cyanidioschyzon merolae*

S. Takahashi, R. Okubo, Y. Kanesaki, B. Zhou, K. Takaya, S. Watanabe, K. Tanaka, and S. Imamura

Plants, Vol. 10, No. 5, 971, May 2021.

Microalgal triacylglycerols (TAGs) are a good feedstock for liquid biofuel production. Improving the expression and/or function of transcription factors (TFs) involved in TAG accumulation may increase TAG content; however, information on microalgae is still lacking. In this study, 14 TFs in the unicellular red alga *Cyanidioschyzon merolae* were identified as candidate TFs regulating TAG accumulation using available transcriptome and phosphoproteome data under conditions driving TAG accumulation. To investigate the roles of these TFs, we constructed TF-overexpression strains and analyzed lipid droplet (LD) formation and TAG content in the cells grown under standard conditions. Based on the results, we identified four TFs involved in LD and TAG accumulation. RNA-Seq analyses were performed to identify genes regulated by the four TFs using each overexpression strain. Among the TAG biosynthesis-related genes, only the gene encoding the endoplasmic reticulum-localized lysophosphatidic acid acyltransferase 1 (LPAT1) was notably increased among the overexpression strains. In the LPAT1 overexpression strain, TAG accumulation was significantly increased compared with the control strain under normal growth conditions. These results indicate that the four TFs positively regulate TAG accumulation by changing their target gene expression in *C. merolae*.

Anonymous Quantum Sensing

H. Kasai, Y. Takeuchi, H. Hakoshima, Y. Matsuzaki, and Y. Tokura

arXiv:2105.05585, May 2021.

A lot of attention has been paid to a quantum-sensing network for detecting magnetic fields in different positions. Recently, cryptographic quantum metrology was investigated where the information of the magnetic fields is transmitted in a secure way. However, sometimes, the positions where non-zero magnetic fields are generated could carry important information. Here, we propose an anonymous quantum sensor where an information of positions having non-zero magnetic fields is hidden after measuring magnetic fields with a quantum-sensing network. Suppose that agents are located in different positions and they have quantum sensors. After the quantum sensors are entangled, the agents implement quantum sensing that provides a phase information if non-zero magnetic fields exist, and positive operator-valued measure (POVM) measurement is performed on quantum sensors. Importantly, even if the outcomes of the POVM measurement is stolen by an eavesdropper, information of the positions with non-zero magnetic fields is still unknown for the eavesdropper in our protocol. In addition, we evaluate the sensitivity of our proposed quantum sensors by using Fisher information when there are at most two positions having non-zero magnetic fields. We show that the sensitivity is finite unless these two (non-zero) magnetic fields have exactly the same amplitude. Our results pave the way for new applications of quantum-sensing network.