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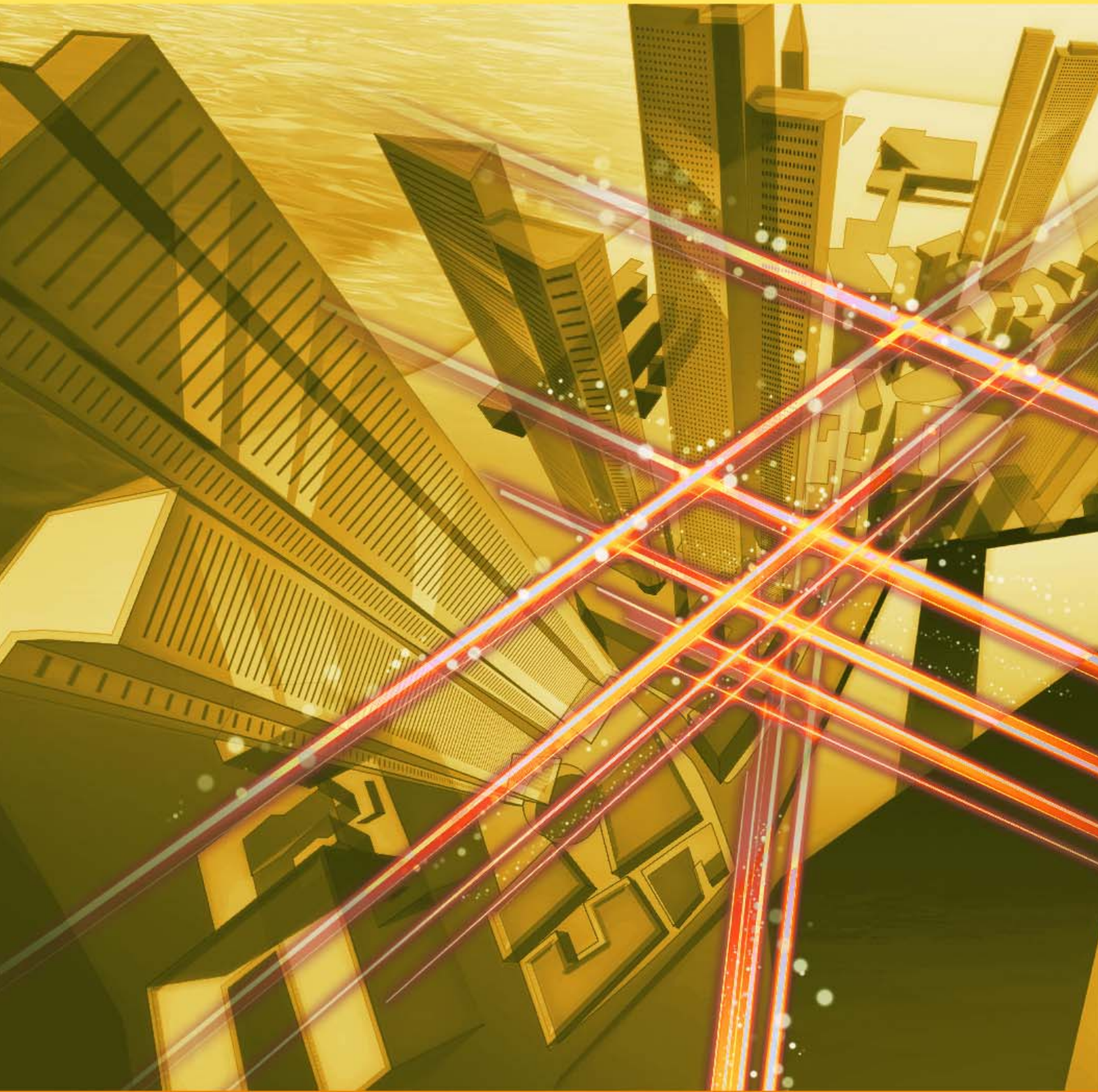

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Global Standardization Activities

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External Awards

I Want to Create New Value and Nurture It until It Becomes Commonplace in Society

Yoshiaki Maeda
Senior Executive Vice President,
NTT DOCOMO

Abstract

On January 1, 2022, NTT Communications and NTT COMWARE became subsidiaries of NTT DOCOMO, starting the new DOCOMO Group. Under the brand slogan, "Changing Worlds with You," the new DOCOMO Group is working together with its customers and partners to create innovations and bring changes to society. We interviewed Yoshiaki Maeda, senior executive vice president of NTT DOCOMO, about strategies of the group's smart life business and his attitude toward work.

Keywords: smart life business, social OS, purpose and values

The growth strategies of the new DOCOMO Group and its smart life business

—Congratulations on your appointment as senior executive vice president. First, could you tell us about the management condition and strategies of the new DOCOMO Group?

Thank you very much. As senior executive vice president, my responsibilities have greatly expanded in addition to those of my previous position as executive general manager of the Marketing Platform Division. Since assuming my new position, my passion for resolving social issues has been increasing, which is energizing me.

On January 1, 2022, NTT Communications and NTT COMWARE became subsidiaries of NTT DOCOMO, forming the new DOCOMO Group. On July 1, 2022, NTT DOCOMO celebrated its 30th year in business. In this milestone year, the new DOCOMO Group integrated enterprise and consumer businesses of the three companies according to function and has made a full-fledged start with the following three segments as pillars of its business. Focusing on mobile-phone services and expanding new services such as fifth-generation mobile communications system (5G) and 5G SA (stand-alone network), (i) the telecommunications business involves reforming sales channels and network structures; (ii) the smart life business aims to increase revenue by more than 120-billion yen year-on-year by accelerating business growth in areas such as finance, payments, and video/entertainment; and (iii) the enterprise business aims to increase revenue by 55-billion yen year-on-year by renovating our portfolio with new services, including the expansion of cloud solutions and by providing one-stop services that integrate mobile, fixed-line, and cloud services. I'm in charge of the smart life business.

NTT DOCOMO launched its 5G services in March 2020, and has been working on implementing 6G. The implementation of 6G is one of the key project

themes concerning the NTT Group's Innovative Optical and Wireless Network (IOWN), and we are aiming to fuse 6G and IOWN technologies under the title "5G Evolution & 6G powered by IOWN." In the "DOCOMO 6G White Paper," we reported that we have developed a platform for enabling human augmentation, which is a new value we will be offering in the 6G era to enhance human senses through networks. This is the world's first platform for human augmentation.

In accordance with NTT Group's environmental and energy vision "NTT Green Innovation toward 2040," NTT DOCOMO has positioned sustainability at the center of its management. Recognizing that tackling climate change is an important corporate issue, we are working to reduce greenhouse-gas emissions from our business activities to zero by 2030. We joined the Science Based Target initiative (SBTi), which aims to limit global temperature rise above pre-industrial levels to 1.5°C, in February 2022. We will promote faster communications and power saving by developing technologies that contribute to reducing greenhouse-gas emissions in next-generation networks and information-processing infrastructure. We will also increase the renewable-energy use ratio of electricity consumed by our business activities to 100%, including the purchase of non-fossil fuels certificates designated as renewable energy.

—What initiatives will be undertaken in the smart life business?

We have introduced an in-house company system and established the Smart Life Company. An in-house company system is an approach to corporate management that treats divisions within a company as independent companies. By increasing the independence of our smart life business, we can make speedy decisions on agile investment and hiring and training professional human resources, which will drive the evolution of our society at an accelerated pace. At the Smart Life Company, we hope to create new value for our customers by connecting multiple partners, delivering that value, and nurturing it until it becomes commonplace in society.

We will first refine the core assets of NTT DOCOMO. For example, our points-based customer loyalty program, "d POINT CLUB," has approximately 90.4-million members. It is by far the largest program of its kind in Japan. That fact should indicate our reliability and stability. What's more, approximately 590,000 partner companies have been nurtured through d POINTs and financial settlements, and the number of d POINT-participating stores has reached 750. We also possess data and technologies such as profiling AI (artificial intelligence), Mobile Spatial Statistics (population statistics using mobile network data), and authentication infrastructure that form the foundation of our various services.

By polishing up these core assets of NTT DOCOMO which support the growth of the marketing domains of our partner companies, we will build a foundation for promoting co-creation and alliances with partner companies, create and provide a group of services that will enrich society, and grow together with our partner companies. In other words, I believe that this is an effort to convert a customer base into a social operating system (OS) to build a platform for transforming society as well as individual lives. This effort involves not only finance, which is our strength, but also other fields that we want to grow and expand, e.g., medical and healthcare, energy, and urban development. In the future, we want to construct a social OS that can provide value from the entire NTT Group in a one-stop-shop manner by using individual identifiers.

I'm with NTT DOCOMO over 20 years and still enjoy working here, never get tired of it

—The idea of constructing a social OS shows the spirit of NTT DOCOMO.

At the Smart Life Company, when we set our goal to work for the betterment of society, we rethought our reason to exist, i.e., our purpose, and our values. We believed that by clarifying and sharing our purpose and values, we could promote corporate growth and move in a positive direction. While we were making these decisions, we kept thinking "who we are and what are we for?" Therefore, we traced our history back to the Nippon Telegraph and Telephone Public Corporation, which was one of the former "three public corporations and five government enterprises" in Japan, and we concluded that our origins lie in the desire to improve Japan during that era. We also reaffirmed that we have always been passionate about making communications and connections between people as well as social evolution a commonplace.

As exemplified by our i-mode (mobile Internet service), by using computing and networks like two wheels of a bicycle, NTT DOCOMO has been a pioneer in providing new value for about 20 years. Across Japan, many people rely on the infrastructure that we provide, and we take pride in our responsibility and capability to provide it. Judging from these achievements, I believe that we have continued to embody "social-value creation." When we launched the Smart Life Company, we clearly stated our purpose is "to connect and nurture until it becomes the commonplace of tomorrow." In accordance with that purpose, we will continue to create and nurture new value in Japan and around the world in the same fashion as we have been doing in cooperation with our partner companies.

We also herald the three values that should be shared to fulfill our purpose, i.e., "There is no end to the pursuit of providing better value," "Think big, act fast," and "The growth of society begins with the growth of oneself." Although there may be days of hardship in the midst of competition, I want to keep challenging myself and remain unwavering to achieve personal growth.

—Your company's purpose and values give us hope for a bright future. How did you develop your powerful and positive attitude?

I feel that the experiences I have had since I started working, and the impact they have had on me have made me the person I am today. When I decided to move from Recruit Holdings to NTT DOCOMO about 20 years ago, my colleagues at the time worried about me saying, "Are you going to be okay?" Despite their worries, I was excited about working for NTT DOCOMO. The reason for my enthusiasm was the fact that at that time NTT DOCOMO had already provided services to tens of millions of customers and had the dynamism to listen to responses from them. At the same time, my mentor, Takeshi Natsuno, the creator of i-mode, often said, "What are you doing this job for? I do this job to make society more convenient, enjoyable, and affluent." I felt a great deal of empathy for his words, and I was proud of what I was doing when I first joined the company. From that time on, I myself had a strong desire to realize that my life was changing and becoming more interesting.

It's been more than 20 years since I started working at NTT DOCOMO, and I've never gotten tired of my work. Over the last 20 years, the world has undergone various evolutions, and each time we have been involved in those evolutions, we have also evolved while creating new things. I feel strongly that I have been able to grow and develop myself as NTT DOCOMO has been evolving and receiving attention from society. It has been an opportunity given to me by NTT DOCOMO for which I am grateful. That's

why I want us to be the kind of company that makes people think, "Wow, DOCOMO!"

Never do things by halves

—I can feel your love for NTT DOCOMO and your passion for your work. Can you tell us what is important to you in your work?

It is said that people who change the world are outsiders, young people, and idiots, and when I joined NTT DOCOMO, I was assigned to a department to which many people had moved in from other companies. Of course, there were also people who had been with NTT DOCOMO and they communicated well with me, and I feel that the trust we built while working together is rock-solid. Based on these experiences, I have two key points I want to emphasize as a top executive. First, I want to run a business that makes everyone who works in it can feel positive possibilities. I want to and must operate the business and practice management that can embody the ideal image of NTT DOCOMO in terms of what sort of presence we can continue to have in society. Second, to manifest the first point, I want all our employees to take responsibility and have the initiative to carry through their work. I myself will always try to communicate with them so that everyone thinks in that way.

Again, for the reasons mentioned above, our purpose and the values to be shared are put in writing. For example, we have listed a series of important messages we want to communicate, such as always having a deep understanding of our customers, focusing on the value for each customer and partner, and meeting everyone's expectations with sincerity and integrity. These messages emphasize the importance of our approach of "Never do things by halves."

There will be many times when you are working that you will think, "That's about right." However, at that moment, your growth stops. I believe that those who are willing to go the extra mile will drive society and ultimately be the winners. In fact, I'm still in the process of growing, and it is difficult to stay motivated all the time. Even so, I'm inspired by those written messages that I keep on my desk. I haven't felt this enthusiasm for a long time.

—I'm sure that your employees also feel their enthusiasm. How does research and development play a role in embodying such enthusiasm?

I have high expectations for research and development. The construction of a social OS using our core assets can be done through the culmination of the wisdom of everyone in research and development. The final form of this system is a social OS that can provide all NTT Group services. I look forward to taking on the challenge of flexibly and promptly addressing the needs of our partners while keeping abreast of social trends by harnessing our assets, namely, the communications technology that supports the network, devices connected to the network, and applications that run on those devices.

I also want us to develop technologies that can provide interesting and enjoyable experiences and worldviews, which mainly concern the entertainment field. I want to use such technologies to create new services in collaboration with our partner companies. Incidentally, Japan's first "smart arena," scheduled to open in Aichi Prefecture in the summer of 2025, is a challenge to create an unprecedented experience of entertainment by introducing cutting-edge technologies. As well as making customers happy in that arena, I want to link that service to new business. Thus, let's do our best to create impactful, sensational, and dramatic experiences.

■ **Interviewee profile**

Yoshiaki Maeda joined NTT DOCOMO, Inc. in 2000. He became director of the Consumer Services Department in 2008, senior vice president and general manager of the Platform Business Department in 2017, and executive vice president and executive general manager of the Marketing Platform Division in 2020. He has been in his current position since June 2022.

I Want to Reduce the Sudden Misfortune Caused by Heart Failures by Bridging the Gap between Medicine and ICT

Shingo Tsukada
NTT Fellow, Bio-Medical Informatics Research Center, NTT Basic Research Laboratories

Abstract

Electrocardiograms (ECGs) are widely used in medical institutions for diagnosis, vital monitoring, health checkups, and automated external defibrillators. With the development of information and communication technology (ICT) and advances in information-processing technologies such as machine learning, the application of ECGs is expanding to self-care and other fields. In today's aging society, the need for in-home medical care and telemedicine using ECGs is rapidly increasing due to the increase in the occurrence of cardiac diseases. We interviewed Dr. Shingo Tsukada, an NTT Fellow who has been conducting interdisciplinary research that integrates medicine and ICT by drawing on his clinical experience as a physician.

Keywords: tensor ECG, hitoe™, interdisciplinary research

Wearable 3D ECG device with new lead system and analysis method: tensor ECG

—It has been three years since our last interview. How are your research activities going?

Things are going well. Using our experience in developing a wearable electrocardiogram (ECG) device using hitoe™ and by combining medical knowledge of clinical ECGs and recent information-processing technology, we are currently constructing a system for constantly measuring and analyzing ECGs. Introduced in 2014, hitoe™ is a functional fabric made by coating a conductive polymer on a cutting-edge fiber material called nanofiber fabric from Toray Industries, Inc. A clothing-type vital sensor using hitoe™ can measure biosignals with high sensitivity without burden on the wearer.

In the process of our research on hitoe™, we were always conscious of ensuring our research results would be practical. The major international sporting event held in Tokyo in 2021 gave us an excellent opportunity to do just that. We have been involved in conditioning athletes taking part in swimming and

cycling competitions by using the advantages of clothing-type hitoe™ capable of sensing vital data during exercise.

To support two swimmers, Takeshi Kawamoto (sponsored by Toyota Motor Corporation) and Ai Soma (sponsored by Miki House), whose training base is the swimming club of Chukyo University, we proposed an exercise program for countering their decline in motor function (centered on the thorax) due to chronic muscle tension associated with their long-term and intensive training. This program promotes awareness of the functional coordination of the spine, ribs, and core muscles in a manner that restores natural and efficient body movement.

In training, changes in the swimmers' streamlined postures before and after participating in our exercise program were evaluated by photographing them from three directions and evaluating ease of breathing, lifting of the arms, and expansion and contraction of the chest circumference during breathing using a multisensor belt equipped with hitoe™ that measures myoelectricity, respiration, and motion. Due to the COVID-19 pandemic, we provided coaching for athlete conditioning via a smartphone-based web-conferencing system. Both Takeshi Kawamoto and Ai Soma were successful at the Japan National Championships, and I am glad that we could continue this initiative despite the pandemic.

We have been involved in the measurement, analysis, and visualization of surface myoelectric potentials for cycling. Using hitoe™ as a bioelectrode, we collaborated with Bridgestone Cycle Corporation and NTT DATA to evaluate pedaling from the perspective of muscle fatigue and muscle activity in top Japanese athletes such as Eiya Hashimoto of Team Bridgestone Cycling. The athletes' surface myoelectric potentials were measured at various locations, including the competition venue for the major international sporting event held in Tokyo, and the pedaling characteristics of each athlete were visualized using the collected measurement data. The visualized characteristics were then fed back to the athletes for discussions based on their intuitions and subjective opinions in a manner that enabled us to identify points for strengthening.

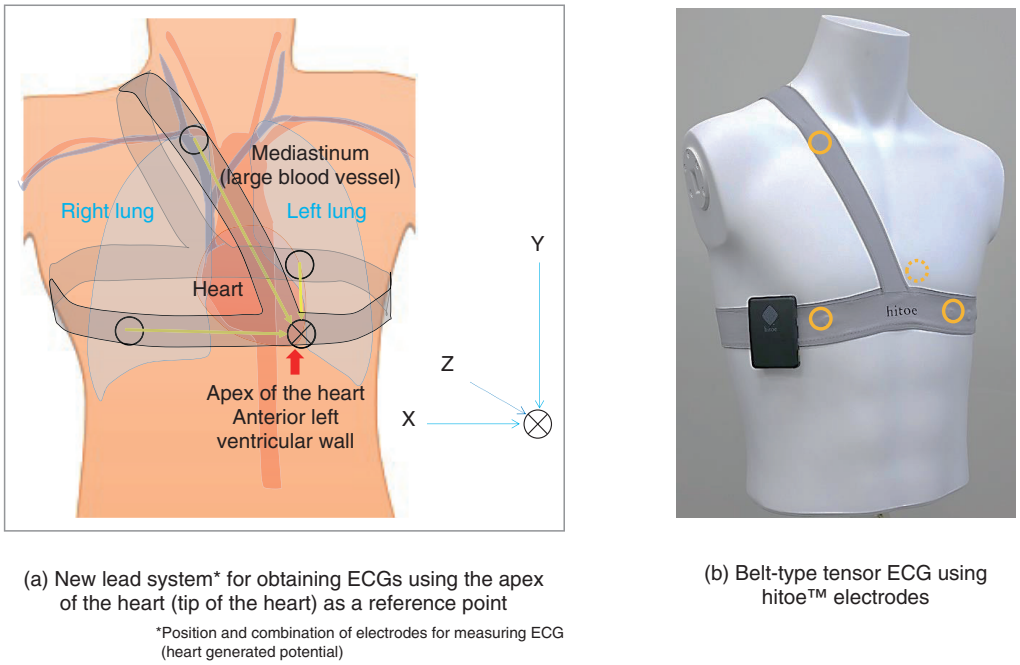
Knowing the status of muscle activity during competition is an important factor in improving and conditioning an athlete's performance. The surface myoelectric potentials measured using hitoe™ can monitor muscle activity from the surface of the body, thus are considered effective for on-site analysis of exercise because they can be measured by having the user simply change clothes in a manner that imposes little burden on the body. Through the above-described initiatives for cycling, we confirmed the usefulness of hitoe™ as a bioelectrode.

—New research themes derived from hitoe™ have been created, right?

Having previously worked as a physician, I joined NTT mid-career in 2010 and started my research in a new field almost from scratch. I was in charge of everything from the invention of bioelectrodes to the creation of fabrics for bioelectrodes that enable constant monitoring of heartbeats and ECGs just by wearing it and implementation of these technologies.

Although we have proposed various bioelectrodes and wearable devices, only a small percentage have been implemented, and other companies are in the same situation. Fortunately, my proposal was a new type of a wearable biometric sensor, so it attracted attention in Japan and from abroad, and I was busy flying all over the world to promote it. In the midst of the stress brought on by that travelling, and because doctors often neglect their own health, I suddenly suffered a heart attack. I was shocked by the ECG obtained using the wearable ECG device that I was studying at the time and by the ECG obtained during the provocation test conducted for precise examination at the hospital. Compared with the intense subjective symptoms I experienced during the heart attack, the abnormality (signal waveform distortion) shown by the ECGs were extremely small.

Regardless of the fact that wearable ECG devices have been studied with the aim of avoiding heart attacks and enabling early diagnosis of heart failure, conventional methods of interpreting an ECG (which are the criteria for determining normal or abnormal ECG) have their limitations. I became aware of the existence of small abnormalities that could be overlooked and cause heart attacks even when using these wearable ECG devices. Overcoming this limitation will require innovative techniques for ECG analysis by using information-processing technology. The behavioral restrictions placed on people due to the COVID-19 pandemic allowed me to change my busy life and take time to focus on this issue and create tensor ECG, a new method of analyzing ECGs.



(a) New lead system* for obtaining ECGs using the apex of the heart (tip of the heart) as a reference point

*Position and combination of electrodes for measuring ECG (heart generated potential)

(b) Belt-type tensor ECG using hitoe™ electrodes

Fig. 1. Tensor ECG.

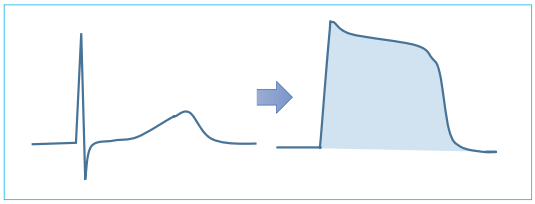
The experience of a clinician and non-specialist in information processing and statistics was useful

—Your unfortunate experience was behind the development of a new method for ECG analysis. Could you tell us more about tensor ECG?

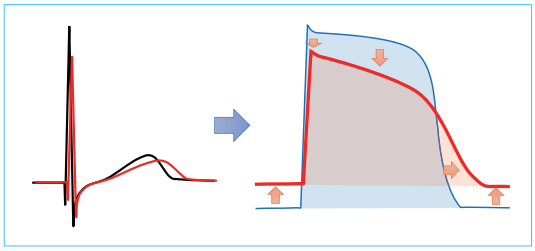
An ECG is a time-varying representation of potential differences acquired from multiple bioelectrodes placed on the chest, extremities, and other parts of the body. The chest electrodes are less affected by body movement, thus produce relatively large cardiac potentials. However, the other electrodes are significantly affected by body movements; accordingly, ECG measurements are basically conducted with the user in a resting state.

To find minute abnormalities in an ECG (i.e., distortion of the waveform), it is necessary to stably record the ECG over a long period. We therefore devised a wearable ECG device with a new lead system, i.e., placing electrodes in three linearly independent directions using the apex region of the heart (i.e., from the apex to anterior left ventricular wall), where the heart is closest to the rib cage, as a reference point (**Fig. 1**). Since the heart and its movement are three-dimensional (3D), a 3D ECG corresponding to the movement of the heart is obtained from electrodes placed three-dimensionally around the heart. To improve wearability of the electrodes and minimize the effects of body movement on the position of the electrodes, the electrodes and wiring are integrated in an elastic belt, which can be easily fitted to the user's body by simply tightening the shoulder and waist belts. We also developed a polygraph (mechanocardiogram) that simultaneously measures cardiac output and deep-vascular pulse waves.

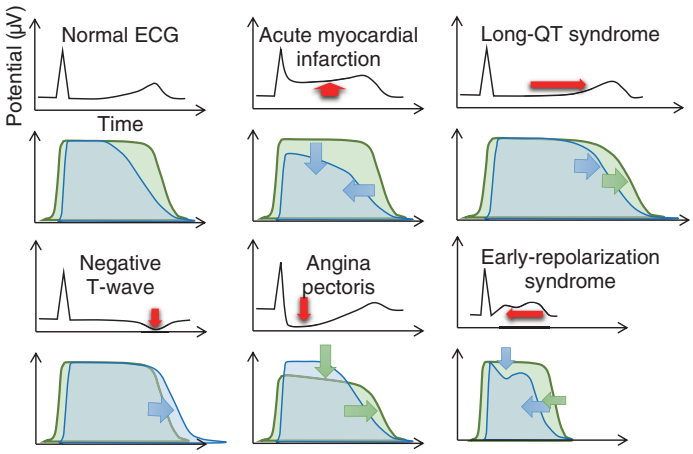
Conventional criteria for normal ECG include a wide range of values for waveforms and intervals, and individual criteria are currently used for each disease or pattern. Even when a person has a heart attack (angina pectoris or other abnormality), their waveform may only be slightly distorted. A method for quantitatively evaluating abnormalities in atypical ECGs has not been developed, and in some cases, abnormalities have been judged to be normal. An ECG is a recording made from the body surface of electrical potentials generated by the excitation (called action potentials) of numerous myocardial cells. The action potential of myocardial cells cannot be measured from the body surface. Therefore, we devised a method of (i) statistically modeling the timing of changes in the action potential by using a Gaussian distribution and (ii) estimating the collective



(a) Normal ECG (left) and action potential of the myocardium (electrical excitation)



(b) Abnormal ECG (red) and distortion of myocardial action potential



(c) Analysis of ECG on the basis of distortion of action potential of the myocardium*

*Tensor ECG is at the research phase, thus cannot be used for medical diagnosis.

Fig. 2. Visualization of cardiac abnormalities by using tensor ECG.

transition of action potentials of the myocardial cells (cardiac muscle) from an ECG. This method makes it possible to resolve, amplify, and visualize atypical distortions in an ECG (**Fig. 2**).

We are currently verifying whether the parameters obtained with tensor ECG are effective indicators for classifying complex cardiac abnormalities and quantifying and evaluating minute distortions in ECGs that have been hitherto overlooked in a unified manner. We hope that this method will be useful for diagnosing arrhythmias (irregular heartbeat) associated with heart failure, ischemic heart disease, and sudden cardiac death.

—Has this type of analysis of ECGs been done before?

I have checked previous papers and prior patents regarding tensor ECG, but I found no similar cases, so I believe the novelty of this development is high. In Europe and the US, where heart failure and heart attacks are the leading causes of death, research in this field is thriving, and competition in research and development has been intensifying as Apple and other companies enter the field. Many of these research efforts use machine learning and artificial intelligence (AI) to automatically determine abnormal ECGs and attempt to detect abnormalities that could not be detected before. However, ECG interpretation using AI faces certain issues, for example, the dependence of the ECG data used to train the AI, ambiguity of causal relationships between ECG data and judgement, and necessity of preparing a large amount of ECG data. The so-called inverse problem in electrocardiography, which involves calculating myocardial action potentials from ECGs and analyzing abnormalities, has been regarded as a difficult problem with no solution. Moreover, abnormalities in ECGs often involve only slight distortions of shape or changes in potential.

However, I know that certain clinicians are good at reading subtle changes in ECGs. I hypothesized that they identify abnormalities on the basis of their experience of examining ECGs of many patients. To solve the above problem, I studied information processing and statistics. The medical science that I studied at university was a far cry from today's information processing, so I had to start from scratch again. However, one day, while relearning about the Gaussian distribution in statistics, I had an inspiration of a very simple model equation and found that it could solve the problem, albeit with some limitations. Perhaps it was my amateur ideas concerning information processing and statistics that worked.

The researcher's mission is to find and nurture new seeds for a new era

—In our last interview, you mentioned that your dream is to develop advanced medical devices for detecting signs of illness, and your dream looks as if it will be coming true very soon.

I do not currently know if tensor ECG is the correct method or useful for clinical medicine. If this method is validated, it would truly be a dream come true as well as a major breakthrough. We are now entering the stress-test phase, and we face a number of technical challenges and must overcome a number of major hurdles before we can start implementing it. We have just started clinical research with tensor ECG, but if its effectiveness and value are recognized, it could be adopted as a method for analyzing ECGs in about three to five years. However, AI diagnosis of ECGs is developing at a breakneck pace, so it is possible that tensor ECG will lose out. Tensor ECG is a versatile analysis method applicable to all types of ECGs. If its clinical efficacy is confirmed, it could contribute to society by enabling precise analysis of a person's ECGs and detection of signs of heart disease by simply clicking on a website in, say, ten years or so.

Academically speaking, I'm considering submitting papers to interdisciplinary journals that cover topics between information processing and medicine. I realize that many of today's research problems cannot be solved by research in a single field of expertise. In fact, in Europe and the US, cross-disciplines or double majors are common—that is, researchers and specialists who have mastered one field of expertise pursue another field of expertise—or work closely with those with another field of expertise to solve problems. However, I feel that in Japan, cross-disciplinary and interdisciplinary studies have not progressed, and such researchers of my generation are few and far between.

My work as a researcher at NTT spans the fields of medicine, physiology, medical engineering, and bioinstrumentation and information processing. I hope to help build a bridge among experts in different fields and address social issues such as rising medical costs.

—What do you value as a researcher?

I believe that the role of a researcher is to find new seeds and nurture them for the next generation. In every field, there are research themes that attract attention at certain times, but not all are necessarily connected to important issues. Therefore, I want to approach my research with an eye to the importance of the theme and the social necessity of research on that theme. While it is essential to enhance one's expertise, I also want to actively engage in interdisciplinary exchanges and hands-on experience. Through various exchanges, I can understand the difficulties and technical bottlenecks in each field, and unique ideas can be born from them. To facilitate such interaction and communication, I hope to continue to be a "handyman" who is easy to talk to, as I said in our last interview.

From my experience as a physician dealing with patients, I believe that happiness is not simply brought by success, achievement, status, and so on; rather, by being blessed with family, friends, and colleagues and interacting with others. This feeling is one that I share with many of the health-care professionals I have worked with. It seems that researchers who have good relationships with those around them are more likely to be able to continue their research activities and achieve more consistent results. Of course, some researchers have achieved remarkable results in their fields of expertise on their own. Research styles can vary individually, but I'd like to continue my research activities while engaging with a variety of people and helping one another.

Researchers are evaluated on the basis of the number of papers they have published, the impact factor of those publications, and other indicators, and I feel that what researchers who have achieved outstanding results have in common is being good communicators. That means they have outstanding communication skills and are well versed in fields outside their expertise; for example, they can relate to topics and difficulties in other fields. I hope to be the same way; that is, I want to continue to conduct research that will lead to a brighter future in a manner that enables my research results to be as much use to society as possible and allows young researchers to have more opportunities to be active.

■ **Interviewee profile**

Shingo Tsukada graduated from Toyama University School of Medicine and received a medical license in 1990. He also received a Ph.D. in medicine from the University of Tsukuba in 2003. He was a visiting researcher at the University of California San Diego from 2003 to 2005. He joined NTT Basic Research Laboratories in 2010 as a research specialist. He has been studying cardio vascular function and neuronal regulation. His current interests include the detection of biomedical signals and functional modification using novel wearable-type and implant-type bioelectrodes based on the composites of conductive polymers with various fibers and textiles. He is an inventor of the textile bioelectrode hitoe™. He is a member of the Physiological Society of Japan, the Japan Society of Applied Physics, the Japanese Circulation Society, the Japanese Orthopedic Association, and the Japanese Association of Rehabilitation Medicine.

Muscle Interface Technology for Augmenting Human Capabilities through Efficient Motor Skill Learning by Electrical Muscle Stimulation

Arinobu Niijima
Distinguished Researcher, NTT Human Informatics Laboratories

Abstract

Conventional motor skill learning has been centered on the visual and auditory senses, but for beginners, acquiring the correct way of using one's muscles like experts takes time. In this interview, we talked with NTT Distinguished Researcher Arinobu Niijima about muscle interface technology for achieving efficient motor skill learning using electrical muscle stimulation.

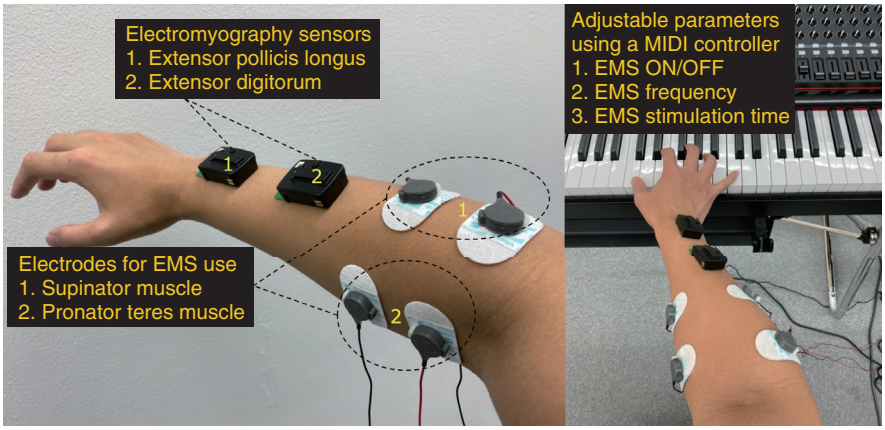
Keywords: muscle interface technology, motor skill learning, electrical muscle stimulation

Muscle interface technology for augmenting human capabilities through efficient motor skill learning

—Dr. Niijima, what exactly is "muscle interface technology for motor skill learning?"

In a few words, "muscle interface technology for motor skill learning" is a system that supports motor skill learning via muscles in sports, playing a musical instrument, and other endeavors. In the research that I'm now engaged in, I'm targeting piano playing. On analyzing the movements made by beginners and experts with sensors, the data obtained shows that the physical movements they make when playing the piano are completely different from each other. One reason why beginners cannot play the piano like experts is that they apply more force than necessary or fail to use their muscles in the right way. With this being the case, I thought about developing a system that, based on these physical differences between beginners and experts, could enable beginners to directly experience the movements of experts by applying electrical stimulation to their muscles.

For example, conventional motor skill learning has been centered on the visual and auditory senses in which an expert may verbally teach beginners how to move their bodies correctly or beginners may simply observe an expert's performance. However, learning an expert's muscle movements by only visual or



MIDI: Musical Instrument Digital Interface

Fig. 1. Example of muscle interface technology for motor skill learning in piano playing.

auditory means can be difficult. The aim of muscle interface technology is to enable efficient learning of correct muscle movement by moving a user's muscles in a more direct manner.

While at university, I played Sports Chanbara and came to teach newly enrolled college students and even elementary school students. It was at that time that I learned that what I first had to teach all beginners was "relax when you swing your sword." Additionally, when I was learning how to swim, the instructor said the same thing: "Please relax." Moreover, when studying how to play the piano from a book, the instruction "Try to relax when playing!" was likewise included. I thought it was interesting that "please relax" was a key point in learning just about any movement. So having some interest in motor skill learning, I began my research thinking, "I wonder if motor skill learning could be supported by computer."

—What kind of method do you use to implement muscle interface technology?

In this muscle interface, we use a technology called electrical muscle stimulation (EMS) to move muscles by electrical stimulation to teach beginners how experts move their muscles. In this regard, a muscle normally contracts by receiving an electrical signal from the brain, but EMS applies electrical stimulation from an external source to the muscle instead of an electrical signal from the brain.

This technology has been traditionally used in the medical field for rehabilitation purposes, but I began my research thinking that EMS has probably never been used as an interface for healthy individuals to learn motor skills. Let me describe how motor skill learning in piano playing can be supported by EMS using **Fig. 1**. In piano playing, there is a technique called "tremolo" in which the player rapidly alternates between two or more keys. For a beginner, this technique is seemingly easy but actually difficult, and as a result, a beginner get tired easily, preventing him or her from playing the piano over an extended period of time. To investigate the reason for this, we used electromyography sensors to analyze how beginners and experts use their muscles while playing the piano. We found that beginners apply more force than necessary to the extensor digitorum and extensor pollicis longus muscles when moving their fingers compared with experts. In contrast, experts use their supinator and pronator teres muscles for wrist rotation instead of using muscles to move their fingers. As a result, they do not get tired easily and can play the piano for a longer period of time. To change the way that beginners use their arm muscles, we created a system that teaches beginners how to play a tremolo while rotating their wrist like experts by applying EMS to the supinator and pronator teres muscles alternately. By practicing with this system, a beginner becomes increasingly aware of wrist rotation instead of finger movements, and with a little practice, learns the knack of playing tremolos for an extended period of time without fatigue.

The key point here is that the beginner moves his or her hand in time with the motion of the electrical stimulation thereby learning in an active manner. In

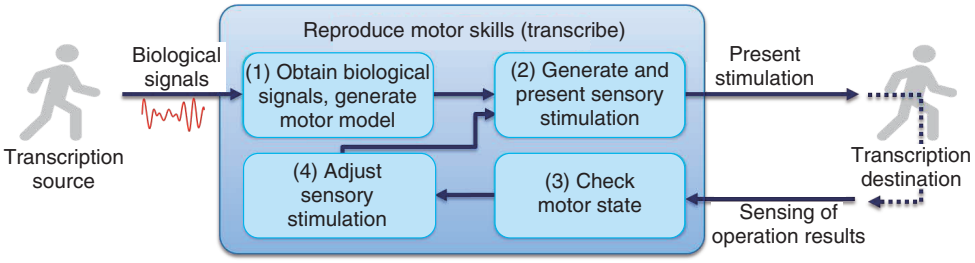


Fig. 2. Outlook for muscle interface technology linked with a human augmentation platform.

this way, motor skill learning progresses, and after practicing, the beginner can play tremolos without EMS using wrist rotation in the right way.

In conventional EMS technology used in human interfaces, there have been many studies on contracting and moving muscles by EMS but there has been practically no research on reducing force applied to a muscle. In contrast, our muscle interface technology indirectly transcribes a relaxed state of specific muscles by applying electrical stimulation to a beginner's muscles based on data obtained on efficient body movement by experts.

The most difficult thing about this research is determining the extent to which complicated movements can be taught. For example, a full-body motion like a golf swing involves multiple muscles, so helping a beginner to learn a golf swing becomes a complicated problem. In such a case, the crux of this research is determining whether expert movements can be taught by applying electrical stimulation to certain muscles to produce certain movements. To this end, we must first obtain knowledge from research fields dealing with physical movement and then collect an extensive amount of information from all sorts of media in addition to the literature. We can then proceed to extract the ways that certain movements should be made common to these sources of information. After this, we can turn biological signals during movements into data using electromyography sensors or motion capture and analyze which muscles are used in what ways. The method of analysis here is not only to look at individual muscle data. A technique called "muscle synergy analysis" can also be used to analyze muscle coordination, that is, to analyze which muscles cooperate with which other muscles. By collecting diverse types of data in this way, we can determine which muscles we should focus on to reproduce expert movements. In addition, we don't stop at this step of collecting data. In the end, it is crucial that we create a system for actually applying electrical stimulation and try it ourselves, and that we conduct subjective evaluations on whether this system will enable users to experience the feeling of motor skill learning.

Future of muscle interface technology in breaking down current barriers

—What is your outlook for muscle interface technology in the years to come?

Figure 2 shows how cybernetics technology such as muscle interface technology that I am researching can be linked to a human augmentation platform for controlling human movement via the network. As a future outlook, I believe that it will be possible to support motor skill learning remotely in real time by using movement transcription technology that copies human movement to another person. This technology transmits data on an expert's body to a beginner at a remote location so that the beginner can receive

stimulation by electrical stimulation equipment.

In addition, I think it would be great if muscle interface technology could be used to extend healthy life expectancy. That is, when a person's muscular strength and cognitive abilities begin to decline with age and what he or she could do when younger can no longer be done, muscle interface technology could be used to synchronize past and present movements by downloading old data and restoring the way that one used to move. When a person stops trying out new things, that person's lust for life will quickly be lost. Supporting one's learning through a muscle interface can overcome the first barrier to skill acquisition and enable people of any age to take up the challenge of doing new things. In this way, I would like to help people with their lives.

—Dr. Niijima, please leave us with a message for other researchers, students, and business partners.

I currently belong to NTT Human Informatics Laboratories, which, as the name implies, is focused on research centered about humans. Engineers and researchers at times tend to focus their efforts on improving technology while leaving people behind. However, if one stops for a moment and considers the actual purpose of research, it is certainly to "improve people's lives and future." As a researcher of human-computer interaction, I myself treat humans as the target of my research, so I can identify with the vision of NTT Human Informatics Laboratories, which I feel to be a very pleasant working environment.

A key strength of NTT is the ability to talk freely with experts in diverse fields within the company. It is said that my research field, human-computer interaction, is a scientific field that is not defined by specialized technology. When I began my research, the knowledge and technology that I needed spanned a wide range. For example, in motor skill learning that I am now researching, not only do I need sensor technology, analysis technology, and engineering skills for combining a series of systems, I also need knowledge related to human movement from the field of neuroscience as well as information on various types of muscles. In short, it is only by gathering such knowledge and technologies from disparate fields that I can research a single theme. At this time, surveying all of this information by myself would take a considerable amount of time and labor, but at NTT, it is easy to ask other researchers for assistance or to hold meetings with them, so specialized knowledge can be acquired in a relatively short time. I also feel that the value of the NTT brand name and the size of the company are amazing. It is often the case that researchers fulfill their role by conducting research, writing papers, and presenting them somewhere at academic societies. At NTT, however, announcing new technologies developed for the good of society draws a response several orders of magnitude greater than usual, which can lead to the actual implementation of those technologies in society. In my opinion, only NTT can provide such a sense of accomplishment and sense of worth.

I've recently noticed that there are young researchers and students that are conducting research while still not knowing what kind of research they personally like. What I have learned over the years in my research is that it's important in the end to do what you enjoy. To give an example, my research during my university and graduate school days was like a short-distance sprint—even if I wasn't particularly interested in that research, it consisted of just short-term objectives, so I gave it my best effort. On the other hand, once I entered adult life as an actual employee, I could imagine my research continuing on for several decades rather like a long-distance run, and I thought that it would be difficult to stick with any research that I had no real interest in. So on thinking on how I could run for such a long distance, I realized that doing something because you truly like doing it could be a powerful driving force. Everyday, there are a variety of things that catch my interest, and it often happens that I begin research on some topic thinking, "This is really interesting!" Of course, a desire to solve social problems is important, but I also think it's important that the individual take a good look at what he or she inherently likes and to verbalize that preference clearly.

■ **Interviewee profile**

Arinobu Niijima received his Ph.D. in engineering from the Graduate School of the University of Tokyo in 2017. He entered NTT in 2012 and is currently a member of NTT Human Informatics Laboratories, where he has been a distinguished researcher since 2021. He is engaged in the research of information-communications and human interfaces/interactions. He is the recipient of the Cyber Space Research Award from the Virtual Reality Society of Japan, the Best Poster Award at Augmented Humans 2021, and other awards.

Supporting a Well-being Society that Integrates the Digital and Real Worlds

Katsuhiko Suzuki and Masaru Miyamoto

Abstract

After reviewing the spread of digital technology in society that has accompanied the development of information and communication technology, this article introduces a well-being digital-real fusion society that is necessary today, and the efforts being made by NTT laboratories to achieve it.

Keywords: well-being, digitization, interdisciplinary research

1. Well-being and digital society

1.1 Well-being as an integral subjective measure

The concept of well-being has been attracting much attention, but why? Let me start by first discussing what is actually meant by well-being. Well-being refers to a state of being in which people are satisfied both physically and mentally [1]. The novel coronavirus (COVID-19) pandemic has adversely affected the well-being of people and is one of the main reasons well-being is considered so important today.

The graph in **Fig. 1** shows how a person's contentment can change over time. We all experience good times and bad times. We believe that well-being is not something that can remedy a bad situation by simply crossing a threshold nor something that is felt only in passing moments but an integral subjective state of mind that takes into account a person's hardships and troubles from the past to the present.

1.2 Well-being in a digital society

To determine what should be done in the information and communication field to promote well-being, we should first examine the current situation regarding the impact that the digitalization of society has had on well-being. Let us look back on the evolution of this digital society in Japan, starting with the founding of NTT's predecessor, Nippon Telegraph and Telephone Public Corporation, in 1952, as shown in **Fig. 2**.

During NTT's early years, from the 1950s to 1980s, fixed-line telephones gradually became widespread. When people wanted to talk to someone far away, they would have to go to the house or room where the phone was, and had to be mindful of the call charges that accumulated as they made their call. It is thought that telephones contributed greatly to the high economic growth of this period in terms of increased productivity.

With the launch of Internet access services in 1996 and the availability of broadband fixed-line networks due to the introduction of optical fiber technology in 2001, coupled with the launch of cellphone services in 1987 and i-mode (NTT DOCOMO's mobile internet service) in 1999, the period from the mid-1990s through the 2000s saw the development of a network environment that was available anytime, anywhere. However, due to the lack of content, this period was recognized as an era when people connected to a network anytime, anywhere whenever necessary.

With the release of the iPhone in 2007 and Android devices in 2008, smartphones and social networking services became widespread, and now, everyone is always connected to a network. Another major change was the widespread switchover to teleworking that was prompted by the COVID-19 pandemic in 2020.

It is important to note that the current era of

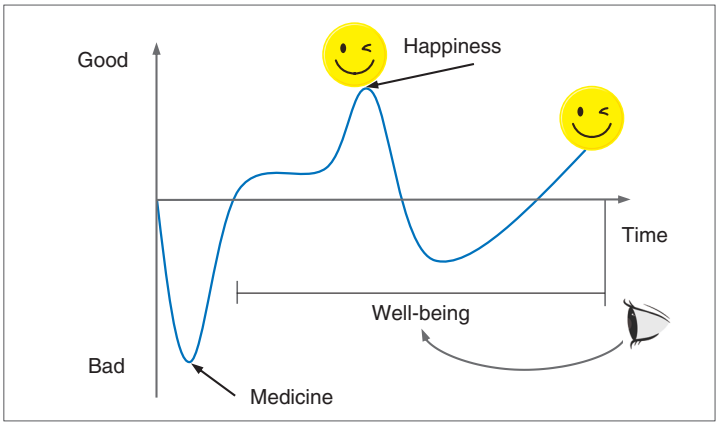
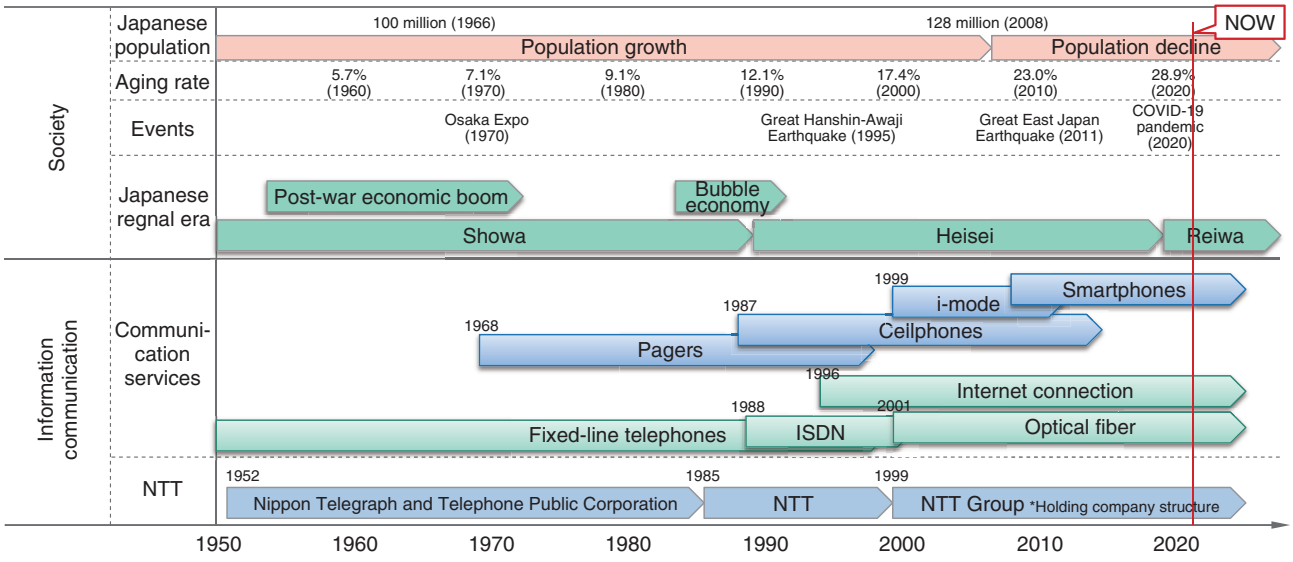


Fig. 1. Well-being as an integral subjective measure.



Aging rate: ratio of the population aged 65 years and older to total population
ISDN: integrated services digital network

Fig. 2. The evolution of digital society in Japan.

constant connection to digital space is only about 10 years old, which is just a fleeting moment in the long history of humankind. It is thought that this state of being constantly connected to digital space for long periods of time could have a significant impact on people's well-being, which is an integral subjective measure based on long-term experience.

Another important factor is Japan's population, which had been increasing after a period of high economic growth, but peaked in 2008 and has since been decreasing due to the declining birth rate and aging population. Against this background, the structure of Japanese society has changed. People now demand new, flourishing lifestyles rather than ever-increasing economic prosperity, and well-being is attracting attention as a result.

1.3 What is required for well-being research

Based on this situation, the requirements our research on well-being should focus on can be summarized with the following three points.

(1) An interdisciplinary approach

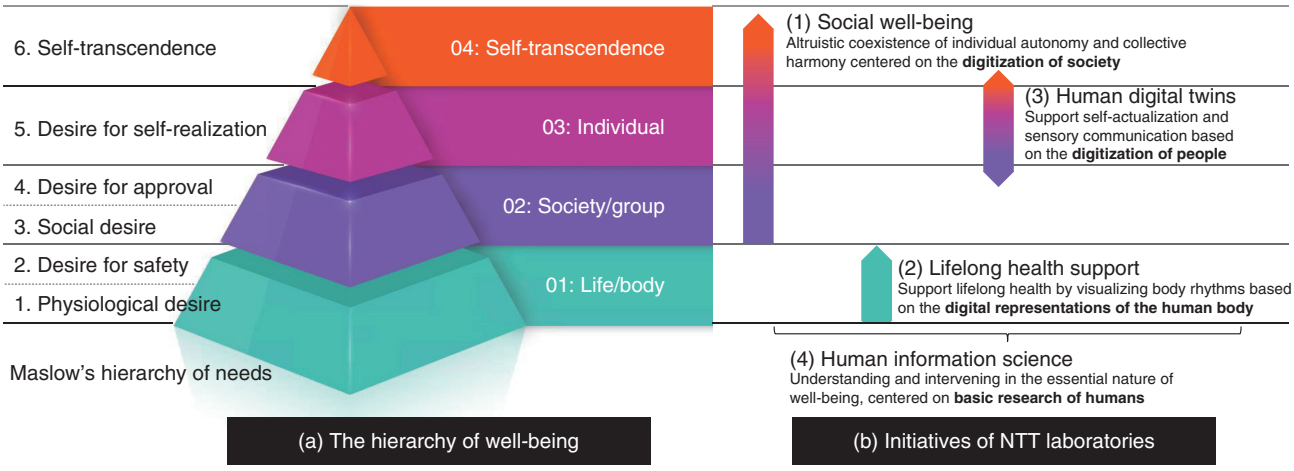


Fig. 3. The hierarchy of well-being and efforts being made by NTT laboratories.

The research must be interdisciplinary. The study of well-being requires not only an engineering approach based on measurement, analysis, and intervention in some form but also an academic approach that includes diverse fields such as psychology, philosophy, ethics, law, and medicine. To achieve this, it is essential to work with experts from universities in addition to collaborating with NTT laboratories personnel having expertise in a wide range of fields.

(2) The pursuit of possibilities through digitalization

Given that digitization has a major impact on well-being, research should be conducted to explore its possibilities. Information and communication technology allows people to establish personalized connections in diverse ways over any distance and can be expected to lead to the creation of new ways of living, working, and learning.

(3) The elimination of obstacles with digital technology

Research is also needed to identify factors that inhibit well-being due to digitization and to suppress these factors. We should respect people's privacy and avoid creating a surveillance society. We should also avoid fueling disparities and divisions through fake news and slander. It is important to bear in mind the negative aspects of digitalization and consider countermeasures.

2. The hierarchy of well-being

Before describing our research into well-being at NTT laboratories, we will first explain the hierarchical structure of well-being since it is a very broad concept (**Fig. 3(a)**). This hierarchy is an extension of what Hiroi [2] described as a hierarchy of well-being based on the hierarchy of needs proposed by the American psychologist Abraham Maslow. Hiroi is mainly concerned with the role of public policies and private companies and the younger generation's awareness of social contribution, whereas in this article, we specifically describe the hierarchy of well-being and its relation to information and communication.

Although we are aware that various taxonomies of well-being have been proposed, and that Maslow's hierarchy of needs theory has its critics, we will use this taxonomy with priority given to ease of understanding and the ability to obtain an overall view of various approaches to well-being, even for newcomers to the subject.

2.1 Life/body

The most fundamental aspect of well-being is the life and body aspect, i.e., being physically healthy and free from life-threatening conditions. Services have been developed that use devices such as smart watches to sense, analyze, and provide feedback on the basis of vital data such as the wearer's heart rate and number of steps taken. Devices that can provide more detailed information on the wearer's physical condition are expected to become more widespread. The characteristics of the human body are universal and do not depend on individuals.

2.2 Society/group

The next layer is the achievement of well-being through face-to-face interaction with groups and social interactions with any number of other people. The development of information and communication technology has made it possible for more people to interact anytime, anywhere, even when they are physically distant from each other. It can also have adverse effects such as social-networking fatigue caused by prolonged connection and social fragmentation caused by slander and fake news.

2.3 Individual

The third layer is the well-being of individuals, whereby people with diverse values can act freely and autonomously in the pursuit of their own goals. Information and communication technology has expanded the possibilities of individual well-being by providing individuals with a variety of choices and means of transmitting information. Well-being in this layer is diverse and subjective.

2.4 Self-transcendence

In his later years, Maslow claimed that there is a self-transcendence layer after the layer of self-actualization that he had previously stated to be the final layer in the hierarchy of needs. The previous three layers basically relate to individual well-being, but this last layer transcends the self and relates to well-being gained by thinking of and acting for the benefit of others apart from oneself (which may include not only people but also things such as specific natural locations and the broader Earth). In a digital society, it is said that centralized platforms can create disparities and divisions by controlling information to suit their own business interests. To go beyond this, it might be worth incorporating a philosophy that values self-transcendence into the governance of platforms.

3. NTT laboratories' approach to well-being

The four approaches to well-being at NTT laboratories introduced in the Feature Articles in this issue are explained in terms of the direction they aim to take and their position in the hierarchy of well-being (**Fig. 3(b)**).

3.1 Social well-being

In our view, social connections constitute the factor with the greatest impact on well-being. However, especially in Japan, doing well within a group of peers (e.g., in a company or at school) can involve sacrificing one's individual goals, so there could be a tendency for groups and individuals to become diametrically opposed. To solve this problem, we are researching social well-being by defining it as a state in which individual autonomy and collective harmony can coexist altruistically [3].

This field is centered on the advancement of digital society, and in the well-being hierarchy, our main focus is on (2) the society/group layer, (3) individual layer, and (4) society/group layer.

3.2 Lifelong health support

With the aim of creating a society where people can spend their entire lives in good health, which is the most basic part of well-being, we are studying how to visualize individual daily data on basic lifestyles (diet, exercise, sleep) so that users can self-adjust their mind/body rhythms in their own way [4].

This field is centered on digital representations of the human body and exists in the life/body layer of the well-being hierarchy.

3.3 Human digital twins

We are studying human digital twin technology that reproduces not only people's external aspects but also their internal aspects, such as their values and thoughts [5]. From an interdisciplinary perspective, we are looking at how this technology can contribute to well-being in the future and not to a dystopia where humans are threatened by artificial intelligence and robots that imitate humans. We are also researching sensory communication that allows people to convey their feelings in digital space.

This field is centered on the digital representation of humans, and in the well-being hierarchy, our main focus is on (3) the individual, (2) society/group, and (4) self-transcendence layers.

3.4 Human information science

Human well-being is diverse and shaped by many factors, including a person's physical and mental conditions, values, and relationships with others. We aim to obtain a comprehensive grasp of these diverse aspects of well-being, understand the human information-processing mechanisms behind it, and study intervention methods that operate on these mechanisms [6].

This field is centered on basic research of humans and positioned as an area that comprehensively supports each layer of the well-being hierarchy.

4. Future outlook

Ever since the Stone Age, humankind has developed by creating tools to make life more convenient. However, it is important to note that the tools we make for our individual needs may, in turn, define and shape our lives. Information and communication technology provides us with important tools that are indispensable in today's world, and since it has become an indispensable infrastructure for daily life, it has a significant impact on our well-being, for better or for worse. We will keep this in mind as we continue our research on well-being, and by conducting research and development and outputting results geared toward delivering a well-being society, we will promote imaginative solutions that actively improve people's well-being rather than simply trying to eliminate things that make people unhappy.

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Katsuhiko Suzuki
Vice President, Head of NTT Social Informatics Laboratories.

He received a B.E. and M.E. in computer science from Chiba University in 1993 and 1995. He joined NTT in 1995 and engaged in the development of a smart card operating system. He is now engaged in the management of the research and development for social transformation and development by combining information science and social science. He is a member of the Information Processing Society of Japan (IPSJ).

Masaru Miyamoto
Executive Research Engineer, Well-being Research Project, NTT Social Informatics Laboratories.

He received a B.E. and M.E. in industrial engineering from Waseda University, Tokyo, in 1995 and 1997. He joined NTT in 1997 and conducted research on user experience and data science by collaborating with various partners for open innovation. His current interest is investigating how telecommunication companies can contribute to a future well-being society.

Social Well-being: Connections that Allow Altruistic Coexistence of Individual Autonomy and Collective Harmony

Masaru Miyamoto, Yoshiaki Nakajima, Yuzo Koga, Yoshiki Nishikawa, Asami Miyajima, Yoshinori Orime, and Shunichi Konno

Abstract

This article describes the concept of social well-being, which seeks to facilitate the altruistic coexistence of individual autonomy and collective harmony in a decentralized society that integrates the digital and real worlds. The article also introduces four initiatives that contribute to the accumulation of knowledge in the humanities and social sciences and a technical platform to promote behavioral change.

Keywords: well-being, decentralized society, design

1. Social well-being research overview

1.1 Problem recognition

In a recent international comparative study of well-being in the workplace [1], Japan ranked 5th out of 116 countries in terms of the number of people who responded that their work significantly improves the lives of others but came very low, 95th, in terms of the number of people who responded that they enjoyed their jobs. These results suggest that the Japanese tend to sacrifice their happiness for the benefit of the group (e.g., society or the workplace). In other words, there is a dichotomy between the interests of the individual and those of the group.

Although the digitalization of society, such as the rapid spread of teleworking caused by the novel coronavirus (COVID-19) pandemic, presents new choices to individuals, it can also increase the above dichotomy due to the effect of filter bubbles[*1] or echo chambers.[*2]

As the social environment undergoes drastic changes such as population decline due to falling birthrates and aging society, people are being expected to become more mobile in their employment, and women and the elderly are being expected to play a greater role in society. However, employment and promotion practices have hardly changed, and the fixed nature of roles and relationships in groups is starting to reach its limit. This is true not only in the workplace but also in schools and families.

1.2 Goal of initiatives

We define social well-being as connections that allow altruistic coexistence of individual autonomy and collective harmony and aim for a society that

*1 Filter bubble: A situation in which someone only hears or sees news and information that supports what they already believe and like, especially a situation created on the Internet as a result of algorithms (= sets of rules) that choose the results of someone's searches (https://dictionary.cambridge.org/ja/dictionary/english/filter-bubble).

*2 Echo chamber: An environment in which somebody encounters only opinions and beliefs similar to their own and does not have to consider alternatives (https://www.oxfordlearnersdictionaries.com/definition/english/echo-chamber).

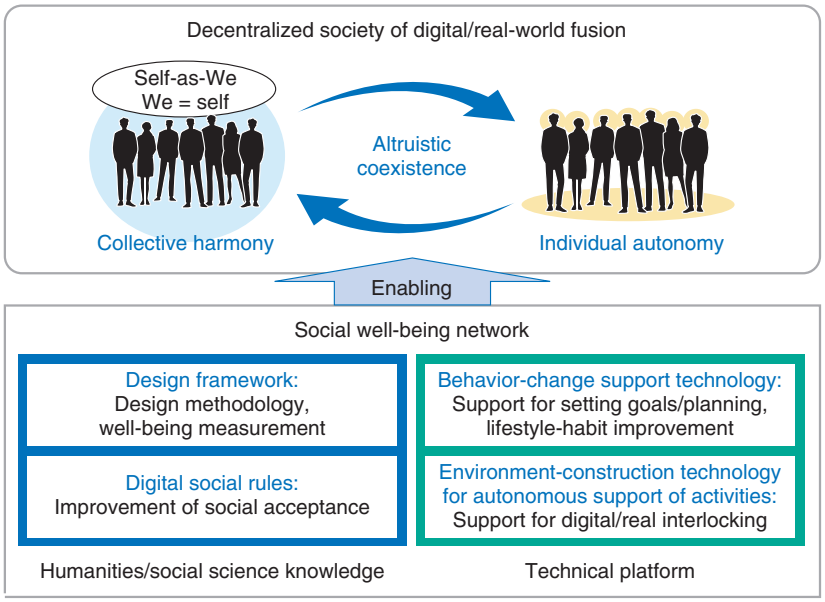


Fig. 1. Social well-being research overview.

enables social well-being. To overcome the dichotomy between individual and groups, it is important that people (individuals) take care of themselves while also being considerate toward and caring for the people and things around them.

1.3 Overview of initiatives

To facilitate such a society, we are developing a social well-being network that consists of a technical platform to promote behavioral change by supporting behavior in the digital and real worlds and the accumulation of knowledge in the humanities and social sciences through practical designs on the basis of theories such as philosophy and sociology. This network is introduced below (**Fig. 1**).

2. Initiatives that contribute to the accumulation of knowledge in the humanities and social sciences

2.1 A design framework for co-creating a well-being society

To achieve a social well-being network, we are researching a well-being design framework. This framework is a design methodology for co-creating services and social mechanisms on the basis of well-being as a new means of measuring value as a replacement for economic growth while sharing values with diverse partners. On the basis of the knowledge from the humanities and social sciences, especially the concept of Self-as-We [2], we are promoting not only theoretical research but also practical research on the design of a social well-being society conducted in daily life. We aim to contribute to the actualization of a social well-being society by establishing a well-being design framework and increasing the availability of opportunities and human resources (**Fig. 2**).

2.1.1 Theoretical research based on the Self-as-We concept

Based on the holistic Self-as-We concept espousing traditional East Asian ideas as advocated by Kyoto University philosopher Yasuo Deguchi, we are conducting research into the definition, standardization, and measurement of social well-being focused on individual characteristics and the quality of relationships between people in groups (fellowship). We are also researching information components and transmission methods for enabling human-to-human connections in digital and real spaces that take the Self-as-We concept into account.

2.1.2 Research on the design of a social well-being society

By focusing on the three aspects of well-being at work (well-working), in the classroom (well-learning), and at home and in local communities (well-bonding), we are working to create new social mechanisms that are free of existing constraints by

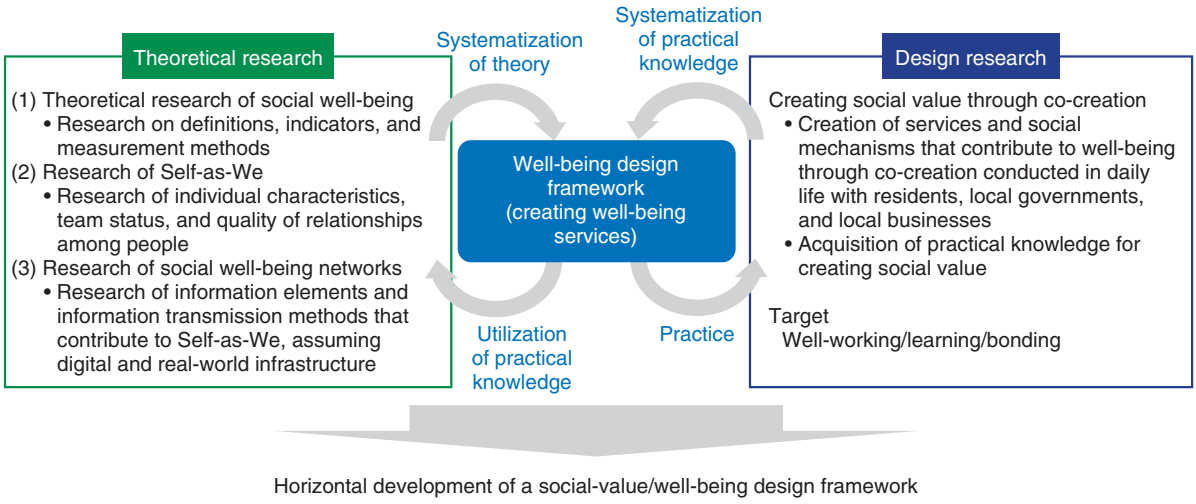


Fig. 2. Design-framework research overview.

engaging in co-creation with partners such as residents, local governments, and local businesses. We are also working on the practical development of tools and processes for building relationships with partners and generating ideas.

2.2 Digital social rules that support well-being

The growth of remote working caused by the COVID-19 pandemic has changed the stereotypical value of *working at the office*. The value of *work-in-life* is now widely recognized, and the technology involved in web-conferencing systems makes this value realistic. As described above, various technologies and services that meet the environmental and situational requirements of society are delivering new values and creating a complex society where people can hold diverse values. However, the rapid spread of new technologies and services can create new problems. For example, the lack of company rules that apply to remote working has given rise to a certain amount of confusion.

However, it is difficult to anticipate issues that might arise when the diverse values of a society and its citizens are updated and to formulate a complete set of rules to address these issues. Therefore, to keep up with changes in the social environment and the emergence of new technologies and services, the ability to repeatedly update these rules within a short timescale while rapidly forming consensus among various stakeholders will be necessary for ensuring the well-being of the forthcoming digital society and its citizens, which is why we are studying how to build consensus for the utilization of data in smart cities.

Smart cities host residents and visitors with diverse values. By acquiring, storing, and analyzing data from various sensing means, it should be possible to provide new value and facilitate better urban development. However, this could give rise to issues with privacy and data rights that are not anticipated by conventional laws and guidelines. Assuming that conflicts may occur among the constituent stakeholders of cities, we are researching how cities, companies, and people with diverse values should cooperate and agree on rules for data use to preserve the respective well-being of groups and individuals.

3. Initiatives that contribute to a technical platform

3.1 Technology to support intrinsic behavior change to contribute to sustainable well-being

To provide long-term maintenance and improve physical and mental health, which is a basic condition of well-being, we are conducting research to support behavioral goal setting and the continuation of behaviors that lead to desirable health habits for each person (**Fig. 3**). By observing people's behaviors and interactions to understand the individual characteristics and conditions that make up each person's personality and carrying out interventions that are tailored for each individual, we are researching means of promoting behavior change through intrinsic

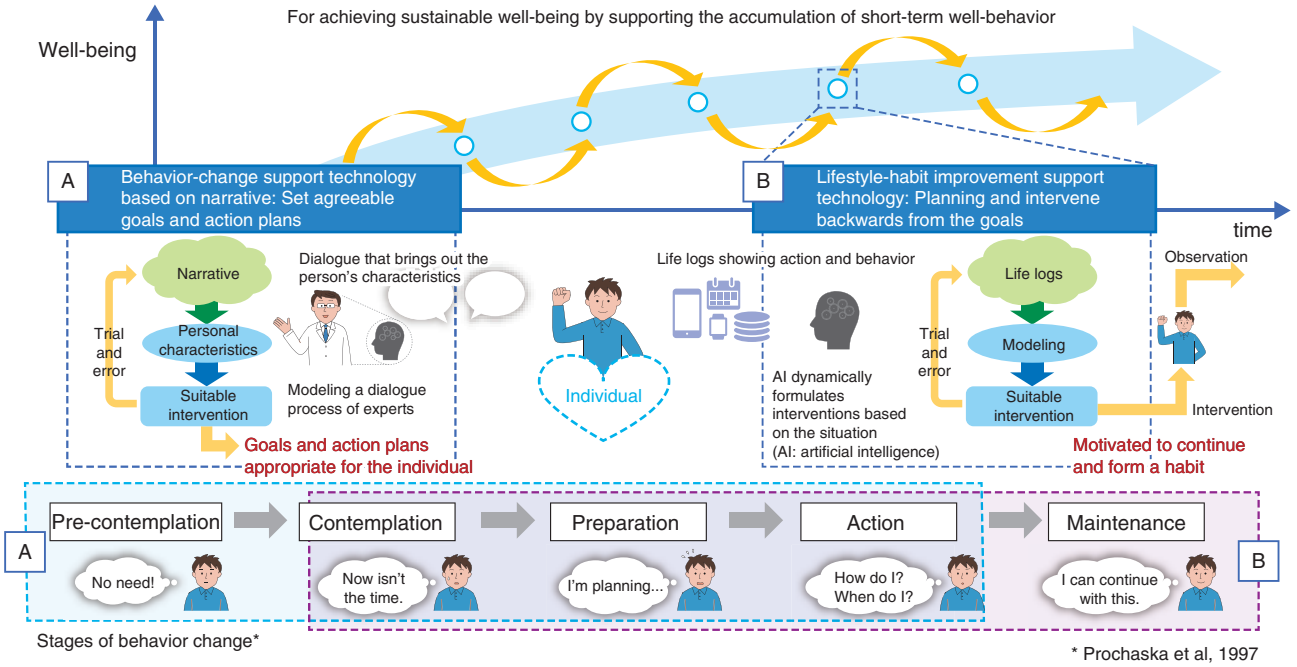


Fig. 3. Overview of behavior-change support technology.

motivation.

3.1.1 Behavior change research based on narrative: Setting goals

With a focus on human narratives, we are modeling individual understanding and intervention methods to promote goal/action planning tasks that are currently carried out by experts through, for example, interviews, and our aim is to systematize some of these models. We are currently developing models of the understanding and intervention processes by analyzing actual health-guidance interviews and subjecting them to expert reviews. As a model of a person-to-person persuasion strategy that motivates people through interventions aligned to their inner values, we plan to verify the effectiveness of this approach in the area of health guidance then consider applying it to other areas.

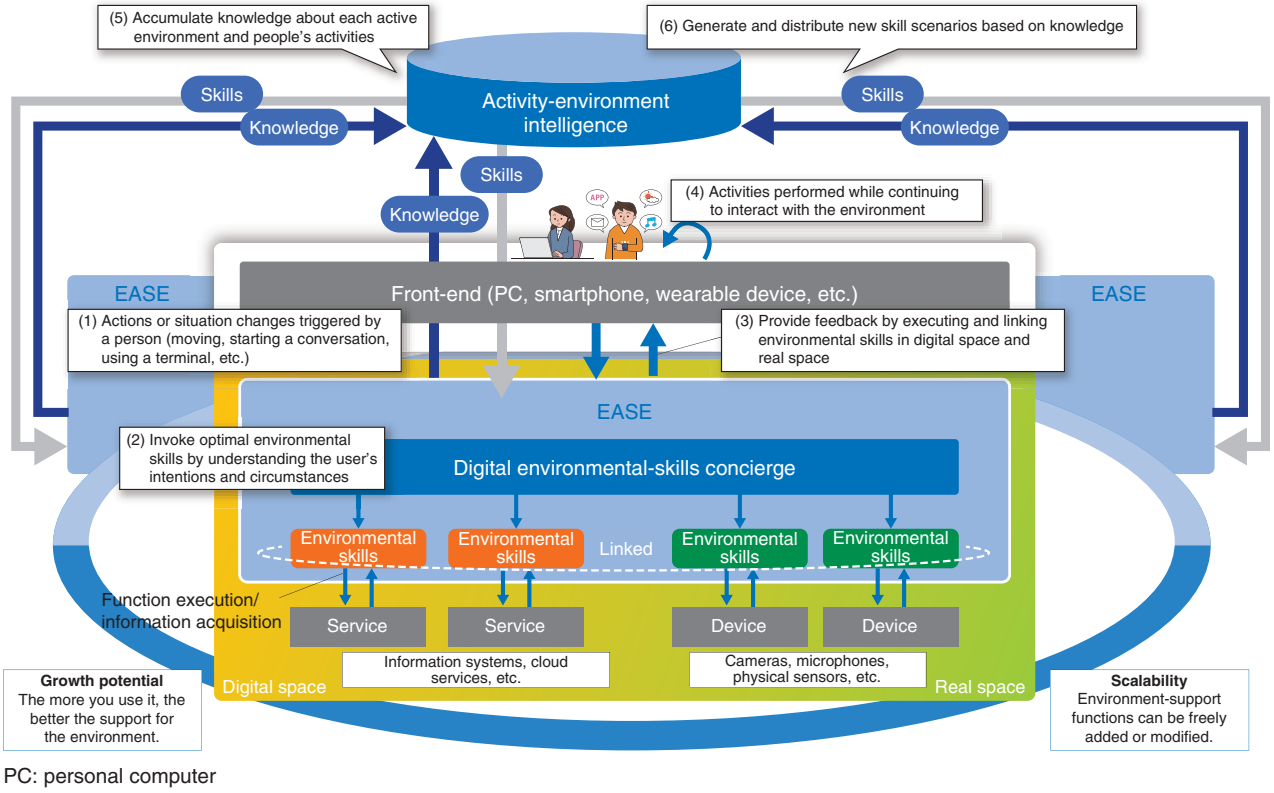
3.1.2 Lifestyle-habit improvement support technology: Planning backwards from the goals

We aim to support the improvement of individual lifestyle habits by modeling behavioral patterns from life logs and providing adaptive action plans to achieve goals. We are currently verifying the effects of interventions for use cases that support the improvement of sleep and exercise habits. We will also consider the further development of applications that help achieve a society where people have self-control over their habits and can take on the challenge of self-realization.

3.2 EASE: Environmental configuration technology that autonomously supports people's diverse activities

As a technical platform for the implementation of social well-being networks, we are researching a technology called Enhanced Autonomous Supportive Environment (EASE) that enables anyone to incorporate the benefits of digital technology in their reality by supporting activities that link digital and real information and functions (**Fig. 4**).

Although each person is an independent self (individual), they also belong to various groups such as companies, schools, families, and social circles. However, when remote working came into widespread use after the outbreak of COVID-19, people ended up having to work at home, making traditional forms of communication more difficult. For example, there are more questions that people have to consider when communicating with others, such as whether this is the right time to talk to the other person, and what means should be used to contact them. This is one of the limitations of current digital technology, and one of the issues that EASE aims to address. EASE will bring diverse digital technologies closer to



PC: personal computer

Fig. 4. EASE, an infrastructure for supporting people.

people, enabling them to communicate smoothly across digital and real spaces, even when the other person is not physically nearby.

EASE consists of three components: (i) environmental skills, (ii) digital environmental-skills concierge, and (iii) activity-environment intelligence.

Environmental skills are a set of functions that support people in using various services and devices across digital and real spaces. The digital environmental-skills concierge makes it possible to not only properly deploy environmental skills to actually support people but also receive feedback from people to improve their support capabilities. Activity-environment intelligence shares information about people in remote locations, such as their knowledge and circumstances, making it possible to provide optimal support for both individuals and groups.

By linking these components, we can, for example, display the presence information of people who are far away, autonomously operate nearby cameras and microphones, and control them in consideration of the user's relationship to the other person (colleague, family member, friend, etc.).

4. Future outlook

We will first focus on work-in-life and regional revitalization and co-create new knowledge, technologies, and business co-creation models through the creation of social values and collaborate with experts in the humanities and social sciences.

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Masaru Miyamoto
Executive Research Engineer, Well-being Research Project, NTT Social Informatics Laboratories.

He received a B.E. and M.E. in industrial engineering from Waseda University, Tokyo, in 1995 and 1997. He joined NTT in 1997 and conducted research on user experience and data science by collaborating with various partners for open innovation. His current interest is investigating how telecommunications companies can contribute to a future well-being society.

Yoshiaki Nakajima
Executive Research Engineer, Social Innovation Research Project, NTT Social Informatics Laboratories.

He received a B.S. in information science and M.S. in mathematical and computing science from Tokyo Institute of Technology in 1995 and 1997. He joined NTT Information and Communication Systems Laboratories in 1997. He has been involved in research and development of information and communication platforms, security platforms, and other areas. He has certifications of Certified Information Systems Security Professional (CISSP), Certified Cloud Security Professional (CCSP), and Registered Information Security Specialist (RISS).

Yuzo Koga
Director, Head of Social Informatics Research Project, NTT Social Informatics Laboratories.

He received a B.E., M.E., and Ph.D. in instrumentation engineering from Keio University, Kanagawa, in 1996, 1998, and 2001. He joined NTT in 2001, and has had several years of experience in designing, building, and operating various communication services including identity management, cloud computing, the Internet exchange point, and the Internet access network. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Yoshiki Nishikawa
Senior Research Engineer, Supervisor, Living Lab Promotion Group, Well-being Research Project, NTT Social Informatics Laboratories.

He received a B.E. and M.E. in computer science from Waseda University, Tokyo, in 1996 and 1998. He joined NTT in 1998 and conducted research on multimedia communication systems and co-creation methods. His current research interests include human computer interaction and social design for a well-being society.

Asami Miyajima
Senior Research Engineer, Supervisor, Well-being Design Group, Well-being Research Project, NTT Social Informatics Laboratories.

She received a B.E. and M.E. in science and technology from Keio University, Kanagawa, in 1998 and 2000. She joined NTT in 2000, where she engaged in the development of medical collaboration systems and security research on cyber-physical systems. Since 2001, she has been researching behavior-change support.

Yoshinori Orime
Senior Research Engineer, Social System Design Group, Social Informatics Research Project, NTT Social Informatics Laboratories.

He received a B.E. in computer science from Saitama University in 1998 and joined NTT Network Service Systems Laboratories the same year. He was involved with network service development and the introduction of cybersecurity measures. Since 2020, he has been engaged in research that incorporates legal matters and social requirements into technical requirements.

Shunichi Konno
Senior Research Engineer, Supervisor, Social Implementation Promotion Group and Group Leader, NTT-CERT Group, Social Innovation Research Project, NTT Social Informatics Laboratories.

He received a Master's degree in information science and technology from the University of Tokyo in 2003. He joined NTT laboratories in 2003 and investigated operating system security, CSIRT (computer security incident response team) operation, and virtualization technologies.

Healthcare Science for Lifelong Health—Visualizing Biological Rhythms and Regulating Them on One's Own

Hiroshi Nakashima, Michiko Seyama, Takuro Tajima, and Kana Eguchi

Abstract

The COVID-19 pandemic has brought dramatic changes to our daily lives and social activities. Anxiety over one and one's family becoming infected, stress caused by limitations imposed on personal behavior, changes in lifestyle, etc. have greatly affected everyone's mental and physical condition. This article introduces health science that aims for a society of lifelong health by visualizing one's daily data covering basic lifestyle habits (eating, exercising, and sleeping) and self-regulating one's biological rhythms.

Keywords: healthcare science, biosensing, biological rhythm

1. Supporting a society of lifelong health

Physical well-being is one basic element of well-being. It is thought that good maintenance of one's physical and mental condition and keeping healthy is important and that good health can act as a basis for cultivating values (symbiosis, empathy, sustainability, happiness, and affluence) that enhance one's quality of life. However, we are experiencing a pandemic on an unprecedented scale in the form of COVID-19. This pandemic has significantly degraded physical and mental well-being throughout the world.

In November 2020, NTT announced its Medical and Health Vision [1] to support lifelong health by predicting a person's physical and mental conditions and acquiring technology to support well-being. As part of this vision, NTT is developing bio-digital twin technology that can sense a massive amount of diverse biological data in a person's daily life, model human physiological functions, and execute simulations for predicting the future by taking individual features into account [2]. The medical field is currently undergoing a paradigm shift from symptomatic therapy that searches for a cure after a person becomes ill to a world of care to prevent an illness from occurring in the first place (preventive medicine). Against this background, NTT aims to conduct digital mapping of a person's biological data and use advanced biological-information-processing technology to create new value, such as avoiding the risk of disease beforehand, inducing healthy behavior to naturally prevent illness, and supporting an individually appropriate self-reliant life.

Amid social changes, such as the trend toward remote working, there have been reports of increasing burden on people's physical and mental conditions due to working in an environment other than one's workplace. There are concerns that a decrease in physical activity or irregular sleep/awake times can lead to the onset or aggravation of lifestyle-related diseases. To maintain one's health, it is common to demand endurance and tenacity to some extent in

managing one's behavior and establishing regular lifestyle habits. We have therefore entered into joint research with Waseda University on the three topics described below in the field of healthcare science with the aim of searching for a behavior-modification protocol for visualizing biological rhythms and enabling automatic regulation without placing a burden on the individual. We are developing techniques for clarifying an individual's biorhythms by arranging lifestyle habits (eating, exercising, and sleeping)—the basic elements of well-being—along a time axis, accumulating biological sensing data accompanying that person's daily behavior, and analyzing those features. We will combine these techniques with knowledge related to behavioral psychology and behavioral economics to establish a mechanism leading to automatic regulation of biological rhythms. This could lead to the development of a technique for presenting and indexing evidence and providing feedback so that a person's health-related behavior can be modified in a voluntarily, effortless manner.

2. Using circadian rhythm to improve dietary habits (in search of chrono-nutrition)

Core body temperature (CBT) has been attracting attention as one index reflecting the circadian rhythm of a person's body. As shown in **Fig. 1**, CBT refers to the temperature of the body's core including the brain and other organs. To keep these organs functioning, CBT is not easily affected by the outside environment and is the highest temperature in the body. CBT rises as a result of an inflammatory response, such as a heat stroke or infectious disease, and drops at the onset of a condition such as hypothermia; thus, it is used as an important vital sign in medicine. CBT fluctuates slightly by about 1°C within the range of normal body temperature in a daily cycle. This fluctuation is linked to the circadian rhythm of every individual [3].

To visualize circadian rhythm based on CBT, NTT has been researching and developing a high-accuracy wearable CBT sensor that can detect this slight daily fluctuation in CBT without placing an excessive load on the body. Medical settings, such as surgery, use measurement methods that involve directly inserting probes into organs, such as the rectum or ear (eardrum temperature), but these methods can place a heavy burden on the patient. In contrast, NTT is using a mechanism that estimates CBT by measuring the flow of heat radiated from the body core, as shown in Fig. 1, to the skin using a sensor attached to the surface of the body [3]. The way in which heat escapes from the body differs in accordance with the outside environment such as wind, temperature, and human activities, but the CBT sensor under development at NTT is equipped with a function for suppressing the effects of fluctuations in the outside environment when the person is in a restful state.

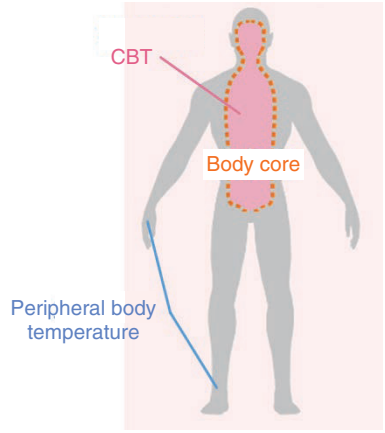

Fig. 1. Peripheral body temperature and CBT.

The biological clock that generates the human circadian rhythm is regulated by the input of information such as external light on a specific brain area (suprachiasmatic nucleus). Recent research has revealed that this biological clock affects the peripheral clocks of various organs such as the liver, kidneys, and muscles, which indicates that the circadian rhythm has a close connection with various states of our body such as metabolism, quality of sleep, exercise, and onset of illness. For example, the level of glucose in the blood when eating can easily increase in the evening hours compared with the afternoon as a circadian rhythm [4]. It is therefore expected that an individual can achieve a healthier dietary lifestyle by ingesting an appropriate meal at the appropriate time given an understanding one's circadian rhythm (chrono-nutrition). In other words, an individual should be able to acquire healthy habits without excessive effort by incorporating nutrition that takes into account this biological clock in one's daily life. Chrono-nutrition has been tested mainly in nocturnal animals such as mice. In our joint research with Waseda University, we are applying NTT's CBT sensor to chrono-nutrition and gathering evidence on the correlation between the diurnal circadian rhythm of humans and a healthy diet.

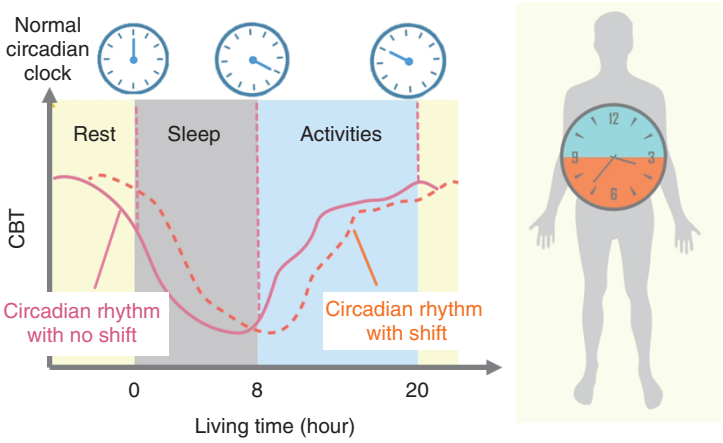

Fig. 2. Circadian rhythm visualized using CBT.

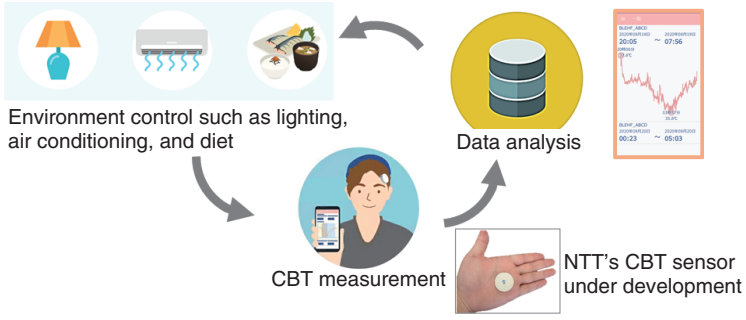

Fig. 3. Example of a healthcare system using CBT measurement.

3. Visualizing circadian rhythm to treat sleep disorders

In today's society in which people's lifestyle habits are becoming increasingly diversified, a shift can easily occur between the circadian rhythm and living time, such as the time that one goes to bed and wakes up, and that this shift is related to the quality of sleep. With no shift between the circadian rhythm and living time, CBT begins to drop several hours before sleep then starts to increase in the latter half of sleep, as shown in **Fig. 2**. However, when a shift does occur between the circadian rhythm and sleep/awake times within one's living time due to an irregular lifestyle, the quality of sleep deteriorates. This state is called *social jet lag*, which is similar to ordinary jet lag to some extent. If left unchecked, this state can lead to sleep disorders such as difficulty falling asleep, light sleep, difficulty in getting out of bed, and sleepiness during the day, which can have a negative effect on one's mental and physical health and social activities [5]. To enable an individual to easily regulate and improve one's quality of sleep, it is important to acquire a technique for one to effortlessly carry out sleep self-management while understanding their circadian rhythm. Applying such a technique should make it possible to construct a healthcare system oriented to the individual, as shown in **Fig. 3**.

We are conducting pilot research on how knowledge of the circadian rhythm obtained from NTT's CBT sensor can help improve sleep quality. We are conducting long-term CBT measurements regarding daily life, and in addition to evaluating biological rhythms obtained from data on the diurnal variation of body temperature, we are conducting correlation analyses with data obtained from a sleep-evaluation wristband, stress-marker tests (cortisol and amylase in saliva), and stress-check questionnaires. Our aim is

to closely track any correlations between temperature patterns obtained from the CBT sensor and stress-marker concentrations or stress indicators, which we hope will lead to methods for evaluating sleep quality and guidelines for improving life.

4. Testing effects of online health and hygiene guidelines on remote workers

Remote working has been expanding since 2020 in the midst of the COVID-19 pandemic. However, a decrease in daytime activities, insufficient exercise, and disruption in one's sleep/awake rhythm due to a life centered on the home can be associated with lifestyle-related diseases and poor mental health. As reflected by comments such as "I can sleep well on days that I move around a lot" and "I feel well-rested with no fatigue after a good night's sleep," nocturnal sleep and daytime exercise are closely related lifestyle habits. Consequently, in this new normal era, it is thought that each person should change their attitude and behavior toward sleep and exercise and that the need for ongoing healthy behavior will increase.

Against this social background, we have begun to study awareness-raising and behavior modification centered on sleep and exercise. As the first step of this study, we are conducting online health and hygiene education seminars targeting remote workers in collaboration with a board certified physician of the Japanese Society of Sleep Research and analyzing their effects. We are using subjective evaluations related to sleep, exercise, and work conditions (commuting to the office or working at home) obtained from questionnaires as well as objective indices related to personal activity (number of steps, calories burned) and body composition (weight, body mass index) obtained from wearable devices or other means. Our aim is to gain a multifaceted understanding of changes in the daily behavior of remote workers. We are also attempting to clarify the changes in daily behavior induced by online health and hygiene education seminars and the relationship between daytime activities and nocturnal sleep. We plan to use the knowledge gained through these studies to investigate techniques for increasing awareness and changing daily behavior for the better in an effortless and sustainable manner. We will also strive to explain any ripple effects of changes in daytime activities and nocturnal sleep in preventing lifestyle-related diseases.

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Hiroshi Nakashima
Executive Research Scientist and Project Manager of Bio-Medical Informatics Research Center, NTT Basic Research Laboratories.

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).

Michiko Seyama
Senior Research Engineer, Supervisor, NTT Device Technology Laboratories and Bio-Medical Informatics Research Center, NTT Basic Research Laboratories.

She received a B.S., M.E., and Ph.D. in applied chemistry from Waseda University, Tokyo, in 1995, 1997, and 2004. In 1997, she joined NTT where she worked on an odor-sensing system based on a plasma-polymerized organic film for environmental contamination and biogas, and a 1-D surface plasmon resonance biosensor combined with a microfluidic device for on-site immunological sensing. Her current interests include development of biosensing platforms for blood components and blood coagulation, including invasive and noninvasive technologies. She is a member of the Japan Society of Applied Physics and the American Chemical Society.

Takuro Tajima
Senior Research Engineer, NTT Device Technology Laboratories and Bio-Medical Informatics Research Center, NTT Basic Research Laboratories.

He received a B.S. and M.E. from the University of Tokyo in 2000 and 2002, and Ph.D. from Tokyo Institute of Technology in 2017. Since joining NTT in 2002, he has been engaged in the research and development of laser photoacoustic spectroscopy and broadband dielectric spectroscopy for non-invasive biomedical sensing. His current research involves multi-modal biomedical analysis using microwaves, terahertz-waves, optics, and ultrasonics. He is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan.

Kana Eguchi
Research Engineer, NTT Communication Science Laboratories and Bio-Medical Informatics Research Center, NTT Basic Research Laboratories.

She received a B.E. from the Kyoto Institute of Technology in 2010, and M.S. and Ph.D. in informatics from Kyoto University in 2012 and 2020. She joined NTT in 2012, and her current research interests include biosignal processing, wearable/ubiquitous computing, medical engineering, and medical informatics. She is a member of IEICE, the IEEE (Institute of Electrical and Electronics Engineers) Engineering in Medicine and Biology Society, the Japanese Society for Medical and Biological Engineering, and the Japanese Society of Sleep Research.

Human Digital Twins for Well-being

Atsushi Fukayama, Shin-ichiro Eitoku, Iwaki Toshima, and Shiro Ozawa

Abstract

NTT is researching digital twin technology that reproduces not only the outer states, such as appearance, voice, and movement, but also the inner states, such as values and thoughts, of humans. To actualize a future in which human digital twin technology contributes to the well-being of people and society, it is necessary to examine the ideal path of technology evolution from a broad interdisciplinary perspective. This article introduces research activities to pursue well-being as the Grand Challenges of Digital Twin Computing, i.e., Another Me and Mind-to-Mind Communication.

Keywords: digital twin, well-being, Self-as-We, Another Me, Mind-to-Mind Communication

1. Toward a human digital twin for well-being

A digital twin reproduces physical entities, i.e., humans, objects, and the environment, on a computer as twins in the digital world on the basis of data collected about such entities. NTT is engaged in research and development for the actualization of various digital twins and their applications from human communication to simulation of cities and transportation [1, 2]. A human digital twin should have not only an external model of a person's face, body, voice, and movement but also an internal model of a person's personality, values, and knowledge. When one hears this, they may be afraid that others would look into their inner self to exploit them or that their existence could be replaced with their digital twin.

To eliminate the possibility of adverse effects caused by the unethical use of human digital twin technologies and pursue ethical advances in such technologies to contribute to the well-being of people and society, NTT has established two Grand Challenges, i.e., Another Me and Mind-to-Mind Communication [3]. A human digital twin should not be used to substitute its original person but facilitate that person's connection with other people and create new opportunities through deep understanding of that person, which would expand the possibility of self-realization and achieve a well-being society based on strong solidarity and altruistic coexistence.

This concept is similar to the Self-as-We theory proposed by our joint research partner, Professor Yasuo Deguchi of Kyoto University. In the Self-as-We theory, a "self" does not mean "I" as an entity that thinks and therefore exists here and now but means "we" that includes all persons who share a purpose or behavior and also objects that support it. Therefore, the "we" that I belong to, i.e., the "self," will change in various ways depending on what goals I am working toward and what activities I am engaged in. A human digital twin that deeply understands the person serves as a bridge that connects that person and others, enabling that person to discover a new self and aim for a better "we" that is open to diversity.

The Grand Challenge Another Me is based on the concept that the digital twin of me that precisely reproduces the outer and inner states of me performs various activities autonomously on behalf of me in the same way as how I would do in those activities (for example, one's digital twin will make friends autonomously in cyberspace), and that by giving feedback with a sense of reality to me, I could expand opportunities in my life, leading to personal well-being such as self-realization.

Mind-to-Mind Communication contributes to a society full of diversity where people can mutually respect each other as well as a society full of creativity in which people's ideas are combined by understanding each person and preventing miscommunication

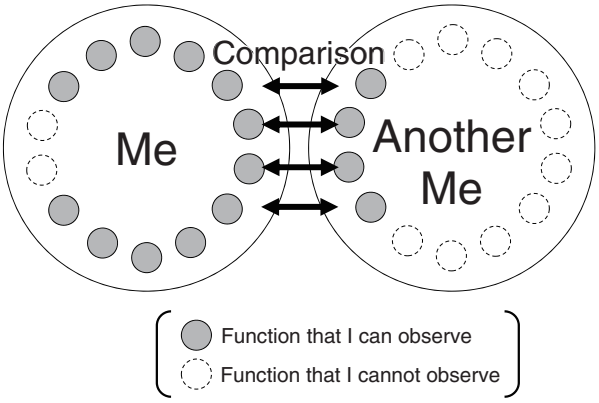


Fig. 1. Functional I.

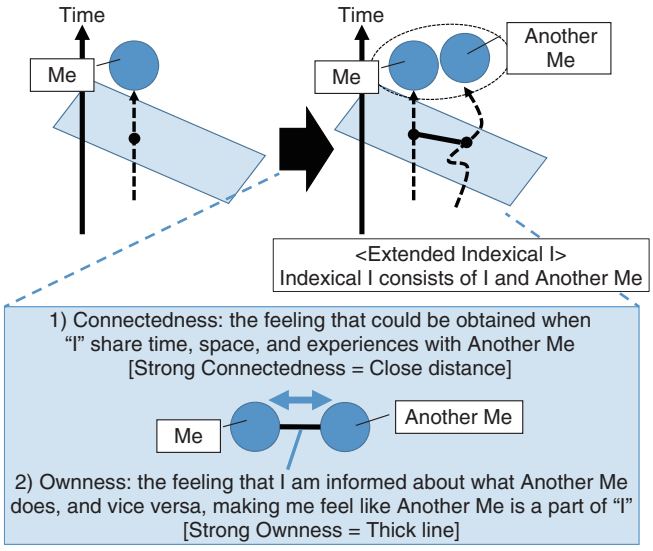


Fig. 2. Indexical I.

(discrepancies in intentions between information sender/recipient) and discommunication (a state in which information transmission itself is missing).

The following is a discussion on well-being in the context of Another Me and Mind-to-Mind Communication.

2. Another Me: another way of being self

Another Me is not an expansion of a uniform person through impersonal artificial intelligence (AI) but an expansion of a person's temporal and spatial potential while maintaining the diversity that each person has. However, depending on the situation in which it is used, there is a possibility that Another Me would replace its actual person, thus degrade the irreplaceability and dignity of that person. What is the desirable position of Another Me in a society that enhances well-being? To answer this question, we are conducting joint research with Professor Yasuo Deguchi and Associate Professor Takuro Onishi of Kyoto University from a philosophical perspective.

After many discussions through collaboration of philosophy and technology, we concluded that Another Me, as an existence having high I-hood but not "I" itself, can be positioned on two axes. The first axis is Functional I (**Fig. 1**), which represents the similarity of what Another Me and "I" can and cannot do. Functional similarity is necessary to allow Another Me to act on behalf of "I." The other axis is Indexical I (**Fig. 2**), which highlights an aspect of "index" that refers to "I" on the basis of certain evidence or a clue found in Another Me that evokes the sensation of "I'm in this now." We discussed that indexicality can be expanded with the Self-as-We theory. If we think "I" and Another Me as a "self" on the basis of this theory, through the sense of "acting and experiencing together with Another Me," we can feel "I" in Another Me. The Indexical I is thought to consist of two further elements. One is "Connectedness," which is the feeling that could be obtained when "I" share time, space, and experiences with Another Me, and the other is "Ownness," which is the feeling that I am informed about what Another Me does, and vice versa, making me feel like Another Me is a part of "I."

To enhance the well-being of Another Me through the expansion of human temporal and spatial possibilities, we believe it is important to enhance both the Functional I and Indexical I elements of Another Me both technically and design-wise (**Fig. 3**).

3. Two communication challenges of Mind-to-Mind Communication technology

Figure 4 shows two communication issues that Mind-to-Mind Communication technology needs to overcome. Figure 4(a) shows a communication scene in which you and your partner have different purposes, backgrounds, and sensibilities. In such a case, communication may not be established in the first place, and discommunication may occur. The purpose of Mind-to-Mind Communication technology is to understand the general meaning. In other words, the goal is to convey, even if vaguely, that there is a

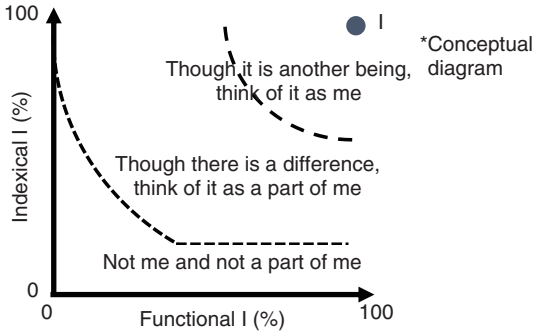
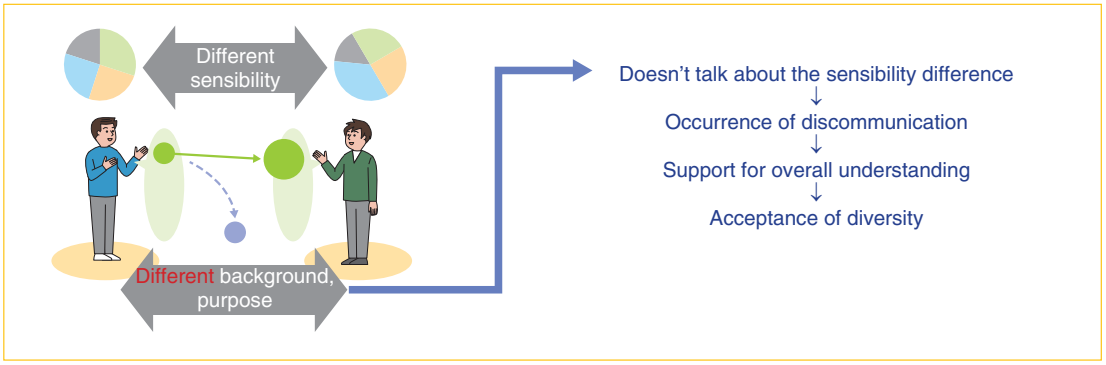
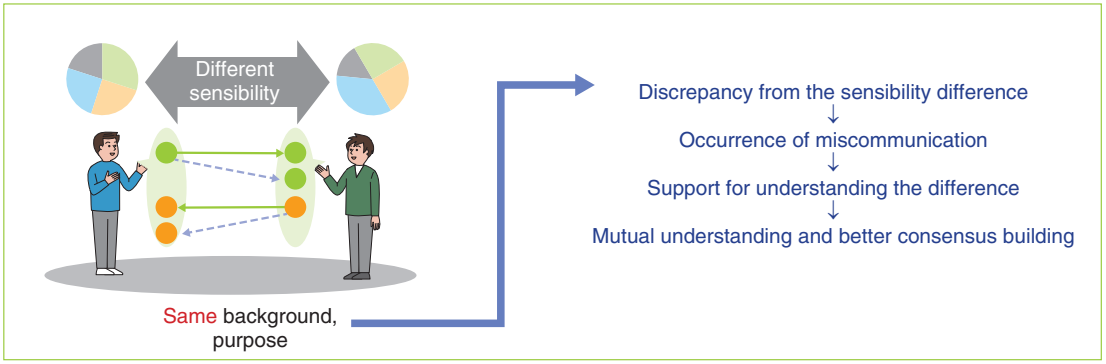


Fig. 3. Proportion of Functional I and Indexical I.



(a) Resolution of discommunication and diversity inclusion



(b) Resolution of miscommunication and mutual understanding

Fig. 4. Challenges of Mind-to-Mind Communication and their effect.

sensibility different from one's own. Even if we do not understand the details of sensibility, if we can sense and recognize that there are various sensibilities, it will promote understanding and acceptance of diversity. Figure 4(b) shows a scene with a common background and purpose and different sensibilities. This occurs often in everyday life. Differences in sensibility lead to miscommunication and misunderstanding. However, if two people with different sensibilities can understand each other for the same

purpose and form a consensus, it will lead to better consensus building and, in turn, increased creativity.

As a use case to promote specific technological development aimed at overcoming discommunication and promoting the acceptance of diversity, we are working to support communication for people with mental disabilities and in minority groups in the workplace. In particular, we are building prototypes of support systems targeting the problem that occurs when each person has a different sensibility, erroneous assumption, and misunderstanding, which could cause problems in the workplace and limit the person's opportunity for active contribution. To visualize and understand well-honed sensibility and enhance creativity beyond differences in sensibility, we have started to convert sensibilities between professionals, such as Shogi (Japanese chess) players and Formula racing teams, and analyze the dialogue and movement between players with different expertise to improve the performance of the individual players. In Shogi, there are no unstable factors for movement due to the environment, and the excellence of agreement and conclusion can be objectively evaluated through recent AI. Because, in many cases, a Formula team deploys two cars with the same conditions in each competition, two drivers with the same conditions and a well-honed sensibility interact with each other from nearly the same environment, allowing them to compare utterances. Although we have only just begun, we are also working to encourage creativity by studying the sensibilities of professionals.

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Atsushi Fukayama
Senior Research Engineer, Group Leader, Another Me Research Group, NTT Digital Twin Computing Research Center.
He received an M.S. in informatics from Kyoto University in 1999 and joined NTT the same year. After working on media-recognition technology, research and development of human-computer interaction technology, and practical application development of network services, he has been leading Another Me Research Group at the NTT Digital Twin Computing Research Center since 2021.

Shin-ichiro Eitoku
Senior Research Engineer, NTT Digital Twin Computing Research Center.
He received an M.E. and Ph.D. in information science and technology from the University of Tokyo in 2006 and 2013. He joined NTT in 2006. His research interests include information systems and multimedia systems for communications.

Iwaki Toshima
Senior Research Engineer, NTT Digital Twin Computing Research Center.
He received an M.E. from the University of Tokyo in 2002 and joined NTT the same year. He then received a Ph.D. in engineering from Tokyo Institute of Technology in 2008. His research interests include human-computer interaction, robot audition, and digital twins.

Shiro Ozawa
Senior Research Engineer, Supervisor, NTT Digital Twin Computing Research Center.
He received a B.E. and M.E. from Tokyo University of Mercantile Marine (now, Tokyo University of Marine Science and Technology) in 1997 and 1999. After joining NTT as a researcher in 1999, he worked for NTT Cyber Space Laboratories (now, NTT Human Informatics Laboratories). His fields of interest are computer vision, video communication, user interfaces, human-computer interaction, and 3D displays. He is a member of the Institute of Electronics, Information and Communication Engineers, the Institute of Image Information and Television Engineers, and the Institute of Image Electronics Engineers of Japan.

Human Information Science Research for Understanding and Improving Our Well-being

Naoki Saijo, Masahiro Fujino, Aiko Murata, Yuuki Ooishi, and Junji Watanabe

Abstract

Our well-being takes on a variety of forms—it can be shaped by many factors such as an individual's physical and mental states, values, and even relationships with other people. We would like to contribute to improving people's well-being by comprehensively grasping such diverse forms of well-being, understanding the human information processing mechanisms lying in the background, and devising intervention methods to act upon those mechanisms. This article introduces our ongoing research on understanding and achieving well-being based on human emotions.

Keywords: emotion, mindfulness meditation, measurement of well-being

1. People's well-being and human information science research

At Human Information Science Laboratory in NTT Communication Science Laboratories, we aim to develop information and communication technologies that enable *heart-to-heart* communication. Thus, we are researching information processing mechanisms involved in perception, cognition, action, and emotion, focusing on the human brain and body from the three viewpoints of information science, psychology, and neuroscience. In everyday life, we feel the world around us through our eyes, ears, nose, tongue, and skin, i.e., our sensory organs, and move our bodies and act upon the world accordingly. Through this interface that we call the human body, we can engage in heart-to-heart communication by accepting another person as he or she actually is and touching that person's heart. Emotions are essential in heart-to-heart communication yet difficult to control as one would like. When receiving the hearts of others, emotions include things that appear unconsciously as a physical reaction (emotional reaction), which, in turn, includes things that one is aware of and recognizes (emotional cognition = feelings). These interact with each other and greatly shape our perceptual experiences and behavior in daily life.

These emotions are deeply involved with our well-being, which is a *vibrant state* that we can vividly feel. They constitute a subjective experience that incorporates an emotional reaction that arises when we receive information from the environment or from another person, and within that, emotional cognition that we can be actively conscious of. In other words, well-being is something that is greatly affected by a transition in emotions. For this reason, it is thought that understanding the mechanisms of human emotions and handling them appropriately can help improve well-being.

2. Research into mindfulness meditation as an emotion control method for regulating physical and mental states

Emotions that change from day to day can enrich our lives at times and make us suffer other times. Coping effectively with these fluctuating emotions and being in a vibrant state is the basis of individual

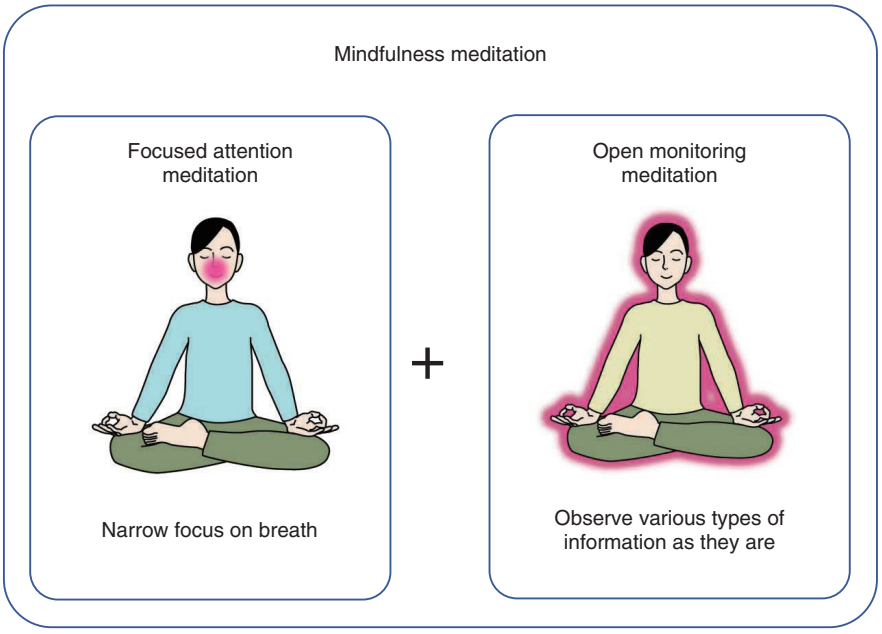


Fig. 1. Focused attention meditation and open monitoring meditation making up mindfulness meditation.

well-being. However, in modern everyday life, full of stress brought on by a rapidly changing environment, information overload, interaction with many people, etc., achieving well-being is not so simple. Under these conditions, *mindfulness meditation* has been attracting attention. Today, an increasing number of companies are introducing meditation as a method for reducing employee stress and improving focus and productivity. Some schools are also adopting it as a method for reducing stress in children and helping them manage their feelings. This, as well as the development of many types of meditation apps, reflect the rapid adoption of meditation in society. Against this background, we are researching the physiological, psychological, and neural mechanisms triggered by the practice of mindfulness meditation with the aim of improving the well-being of people by establishing new intervention methods based on scientific knowledge.

3. Physiological basis of stress-reduction effects caused by mindfulness meditation

The awareness that arises from paying attention in the present moment, and non-judgmentally is called *mindfulness*. Mindfulness meditation, which seeks to achieve this state, is a form of mental training that begins by focusing one's attention on a single target, such as one's breath, then gradually expanding to various senses, feelings, and thoughts. The aim is to control one's attention and emotions without being swayed or confused by those targets of attention. Many studies have shown that this form of meditation can effectively reduce stress, prevent recurrences of depression, and improve well-being.

The physiological mechanisms behind this reduction in stress by mindfulness meditation have remained unclear. Autonomic activity and concentrations of stress hormones have been used as indicators for measuring stress, but the effects of mindfulness meditation on these physiological indicators have been inconsistent. Therefore, we looked at mindfulness meditation as a combination of two meditation methods: *focused attention meditation* for focusing one's attention on a single target and *open monitoring meditation* for recognizing various senses, feelings, and thoughts as they are [1] (**Fig. 1**). We hypothesize that the effects of either one or the other meditation method was presented or the effects of both was presented in mixed form in previous studies, which suggests that inconsistencies would likely appear among those results.

We developed a 30-minute period of instruction for both focused attention meditation and open monitoring meditation that would enable even people with no experience in meditation to practice each method. We

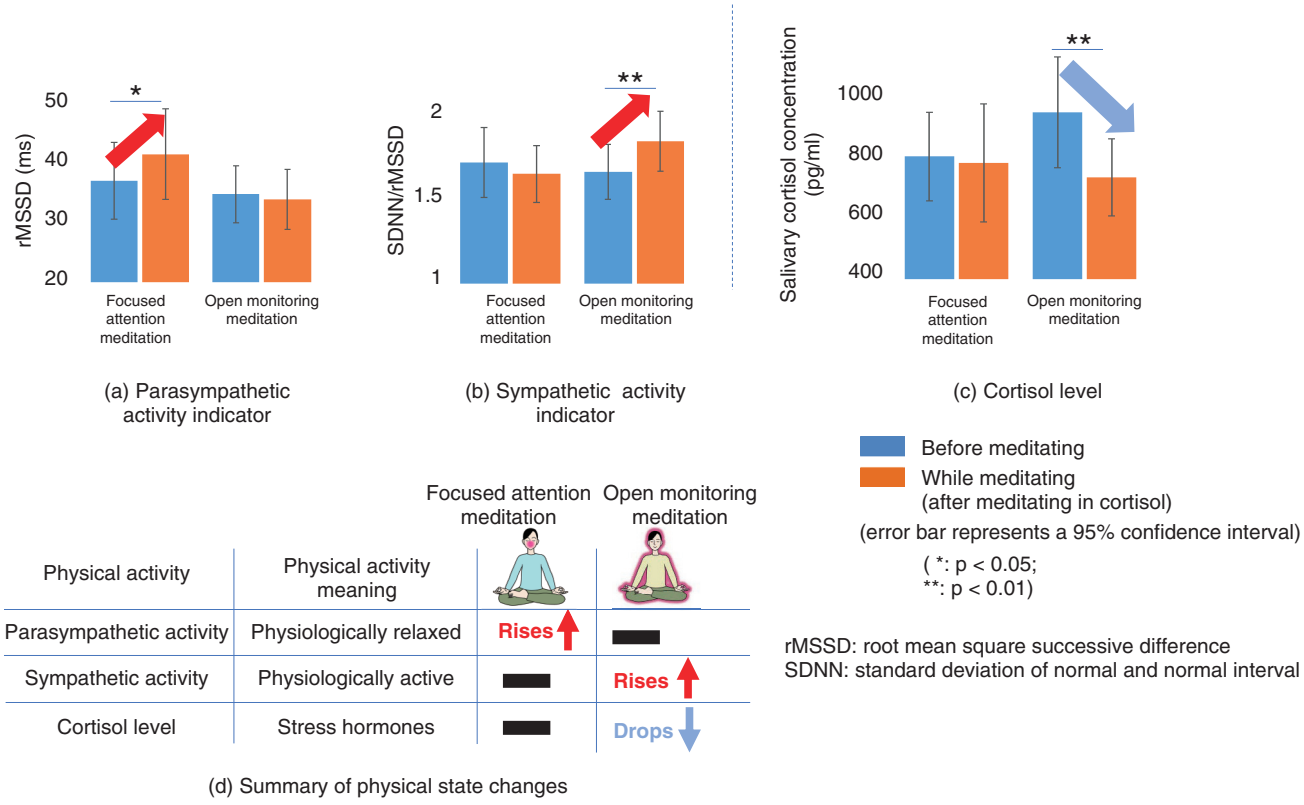


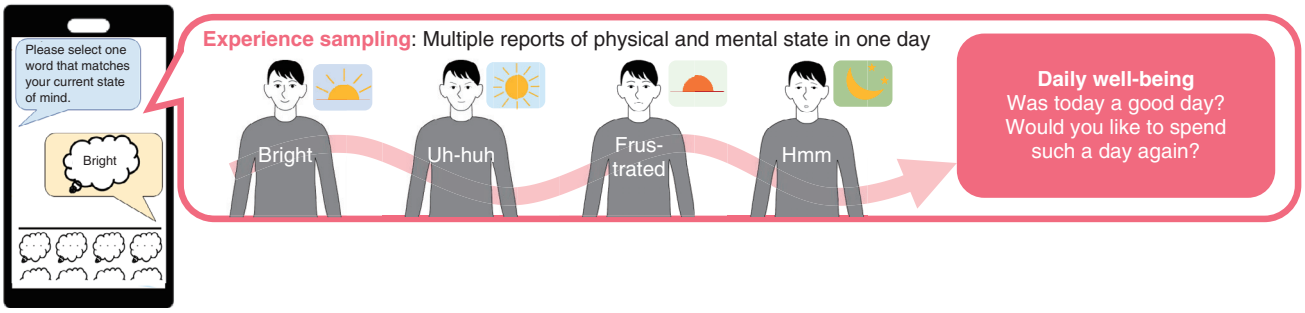
Fig. 2. Changes in physical state caused by mindfulness meditation.

then investigated changes in participants' physiological stress levels caused by focused attention meditation and open monitoring meditation. The results indicate that focused attention meditation triggered a rise in parasympathetic activity, the physiological basis of relaxing (**Fig. 2(a)**). Open monitoring meditation, however, started an increase in sympathetic activity, the physiological basis of arousal (**Fig. 2(b)**), and a simultaneous drop in cortisol level, which is said to be a stress index (**Fig. 2(c)**). These results can be interpreted to mean that focused attention meditation has the potential of ridding oneself of distracting thoughts and enabling relaxation by focusing on a single target. During open monitoring meditation, in contrast, people's arousal level is high because they experience various senses, feelings, and thoughts, whereas their stress is reduced because they experience them as they are (**Fig. 2(d)**). Therefore, it has been shown that focused attention meditation and open monitoring meditation activate different physiological mechanisms and contribute to stress reduction in different ways [2].

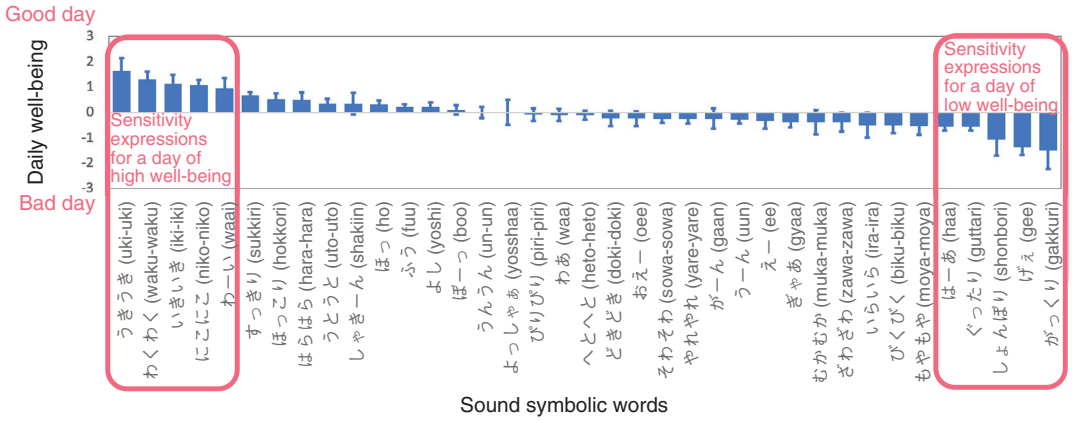
By effectively combining focused attention meditation and open monitoring meditation, the possibility arises of improving our well-being on our own by appropriately controlling our inner state as in making changes to autonomic activity, hormone levels, etc.

4. Measuring diverse factors in everyone's well-being

Our well-being takes on diverse forms—it is not determined solely on the basis of an individual's physical and emotional states. It can also change according to what a person values and how that person understands his or her relationships with other people, the environment, etc. In short, a multifaceted approach must be taken to obtain a deeper understanding of well-being. With this in mind, we are devising original techniques for measuring (1) changes in self-reported physical and mental states, (2) values that need to be satisfied for oneself, and (3) the way in which people perceive the relationships with others (idea of self), and testing the validity of each of these techniques.



(a) Procedure for recording sensitivity expressions several times a day using a mobile terminal



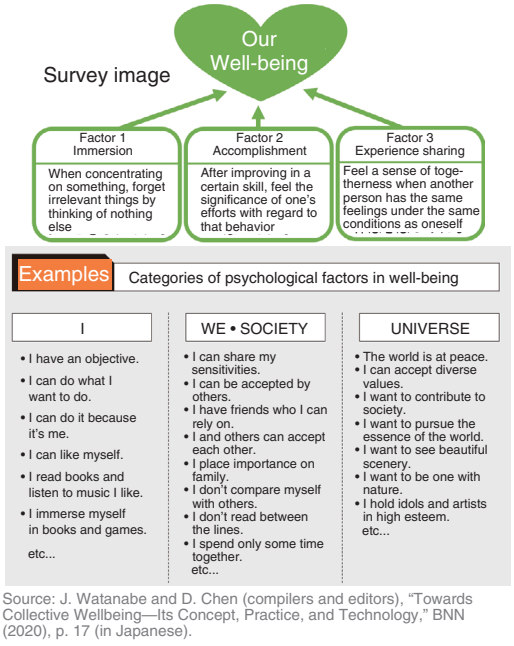
(b) Relationship between daily well-being and sensitivity expressions

Fig. 3. Experience-sampling method using sensitivity expressions.

4.1 Intuitive and embodied experience-sampling method for monitoring physical and mental state transitions

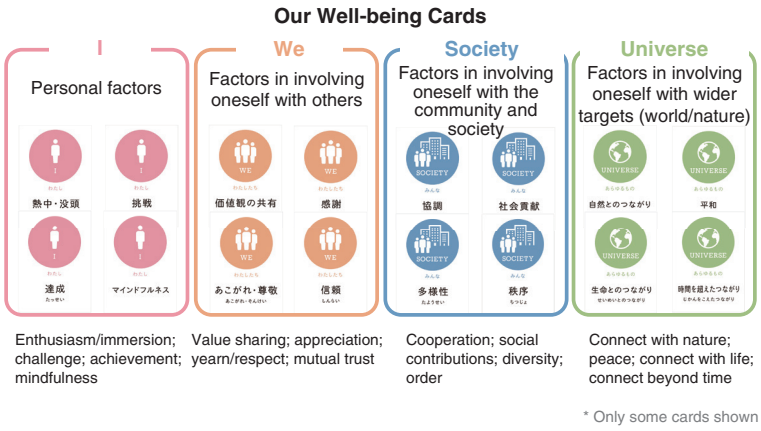
Emotions have aspects of physical emotional reactions and subjective emotional cognition, so to learn about the inner state of an individual, it is necessary to measure changes in that person's subjective mental state in addition to objective biological indicators such as hormone levels and autonomic nerve activity. One technique for evaluating subjective physical and mental states is the experience-sampling method. This method is a research procedure for monitoring ever-changing subjective emotions, thoughts, feelings, behaviors, etc., with respect to a particular event at that instant or shortly after. This self-reporting is performed several times a day, so a method that makes for easy and intuitive replies is desirable. Therefore, we decided to use sound symbolic words and interjections in Japanese, which can be considered subjective expressions with embodied intuitions [3]. This method records one's emotions at a certain moment several times a day using such words, e.g., "doki-doki," used in a sense similar to the English "thump-thump," and interjections such as "waai" used in a sense similar to the English "wow," which makes it possible to examine transitions in subjective mental state with a minimal cognitive load on the user (**Fig. 3(a)**).

On actually using this method to investigate the relationship between daily changes in mental state and well-being (16 subjects × 4-week survey), and taking as an example a day that participants thought of as "a really good day" (high well-being), we found that there were many replies such as "uki-uki (うきうき)" indicating good expectations of the future or "iki-iki (いきいき)" and "niko-niko (にこにこ)" reflecting a positive state compared with replies like "yosshaa (よっしゃあ)" indicating instantaneous joy (**Fig. 3(b)**).



Source: J. Watanabe and D. Chen (compilers and editors), "Towards Collective Wellbeing—Its Concept, Practice, and Technology," BNN (2020), p. 17 (in Japanese).

(a) Categorization of free descriptions based on survey



(b) Creation of 27 cards based on those categories.

Fig. 4. Creation of Our Well-being Cards.

4.2 Tools for visualization and sharing values

Things that are important to ones or mentally satisfy oneself differ from person to person. The first step toward respecting and achieving diverse forms of well-being is to remind oneself of one's values and notice similarities and differences between these values and those held by surrounding people, thereby fostering mutual understanding.

We conducted a questionnaire-based survey targeting about 1300 people asking them to write down three things "important to you" and categorized the approximately 3900 replies obtained (**Fig. 4(a)**). We found that we could categorize those replies into things concerning oneself (I), things concerning involvement with other people (We), things concerning involvement with the community and society (Society), and things concerning the world, nature, and other broad subjects (Universe) [4]. We then extracted main factors from those four categories and created 27 "Our Well-being Cards" (**Fig. 4(b)**) [5]. These cards can be used as a tool for promoting awareness of what values one and surrounding people hold.

We have used these cards in a workshop targeting elementary school students. Groups of students shared what was important to each in terms of well-being then devised a travel plan that could achieve well-being for all members of the group.

The students commented that "I was surprised that some things were the same as those of other students while other things were different" and that "The story of a trip can grow infinitely when other people are present." We found that such an activity could promote mutual recognition of diverse values.

4.3 Measurement of holistic idea of self—Self-as-We

It has been pointed out that how one perceives oneself in relation to others, that is, one's *idea of self*, differs according to culture and the individual. In collaborative research with Professor Yasuo Deguchi, a philosopher at Kyoto University, we developed the Self-as-We scale to quantitatively evaluate the Self-as-We concept proposed by Professor Deguchi on the basis of a technique in psychology for measuring personal characteristics [6].

The conventional idea of self is that "I" myself can exist in an autonomous manner since I can manipulate tools and control my environment even without having to interact with other people. However, Self-as-We views "we" consisting of everything such as other people and the environment as "self" and

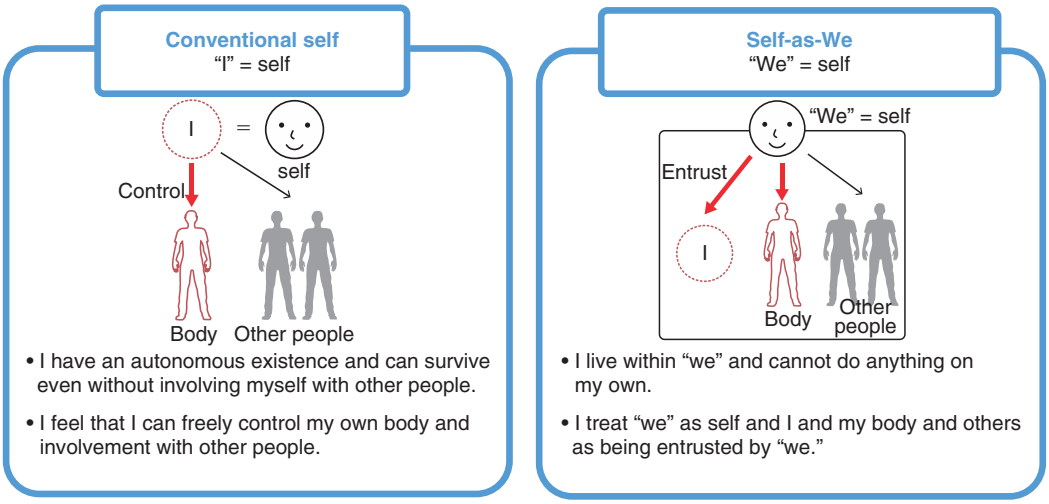


Fig. 5. Self-as-We. Concept of conventional self (left) and Self-as-We (right).

considers “I,” as a member of “we,” to be entrusted by “we” for some of the same actions as other people and things (**Fig. 5**). In other words, people and things within “we” can be viewed as equals deserving of respect. The Self-as-We scale quantifies such involvement with the environment and other people through a multi-item questionnaire.

On surveying the relationship between mental health and the idea of self during the COVID-19 pandemic using the Self-as-We scale, we found that people who were more strongly inclined to have a Self-as-We view were less likely to be depressed, that is, they were in better mental health [7].

5. Conclusion

To contribute to improving our well-being, it is necessary to understand the underlying mechanisms of human emotions and understand and act upon diverse forms of well-being comprehensively. Going forward, we will continue to research human information science to understand and improve people’s well-being from various viewpoints including psychology, neuroscience, information science, philosophy, and design.

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Naoki Saijo
Senior Research Scientist, Supervisor, Sensory Resonance Research Group Leader, Human Information Science Laboratory, NTT Communication Science Laboratories.
He received a B.E. and M.E. in mechanical engineering from Waseda University, Tokyo, in 1999 and 2001, and Ph.D. from Tokyo Institute of Technology in 2010. He joined NTT in 2001 and has been engaged in research on human information processing, including mechanisms of human sensorimotor control and motor learning. He has recently been focused on the interaction mechanisms of human emotion and action, especially in highly skilled people such as athletes and performers. He is a member of the Society for Neuroscience (SfN), the Japan Neuroscience Society (JNS), and the Institute of Electronics, Information and Communication Engineers (IEICE).

Masahiro Fujino
Research Specialist, Sensory Resonance Research Group, Human Information Science Laboratory, NTT Communication Science Laboratories.
He received a B.B. from Kobe University, Hyogo, in 2002, and B.Ed., M.Ed., and Ph.D. in education from Kyoto University in 2014, 2016, and 2019. He joined NTT in 2021 and has been engaged in research on human information processing, including mechanisms of human attention control and emotion regulation induced by mindfulness meditation. He has recently studied the mechanism and effect of observing natural breathing on well-being. He is a member of the Japanese Psychological Association (JPA), Japanese Association of Mindfulness, and Japanese Association for the Study of Buddhism and Psychology.

Aiko Murata
Research Scientist, Sensory Resonance Research Group, Human Information Science Laboratory, NTT Communication Science Laboratories.
She received a B.A., M.A., and Ph.D. in human sciences from Hokkaido University in 2009, 2011, and 2016. She joined NTT in 2018 and has been engaged in research on human information processing, including mechanisms of human empathy and well-being. She has recently studied the interaction mechanisms of human emotions and personal and social well-being using subjective and physiological measures. She is a member of JPA and Japan Cognitive Science Society (JCSS).

Yuuki Ooishi
Senior Research Scientist, Sensory Resonance Research Group, Human Information Science Laboratory, NTT Communication Science Laboratories.
He received a B.S., M.S., and Ph.D. in physics from the University of Tokyo in 2003, 2005, and 2008. He joined NTT in 2008 and has been engaged in research on human information processing, including mechanisms of human emotion induced by sounds or music. He has recently studied the mechanisms of human emotion, including the effects of mindfulness meditation, parents-infant interaction, and auditory-tactile interaction. He is a member of JNS.

Junji Watanabe
Senior Distinguished Researcher, Sensory Resonance Research Group, Human Information Science Laboratory, NTT Communication Science Laboratories.
He received a Ph.D. in information science and technology from the University of Tokyo in 2005 and joined NTT in 2013. His research is focused on haptic communication and collective well-being. He concurrently works at NTT Social Informatics Laboratories and NTT Human Informatics Laboratories.

Communication Science that Adapts to the Changing Present and Creates a Sustainable Future—Aiming to Create Technology that Brings Harmony and Symbiosis among People, Society, and the Environment

Futoshi Naya

Abstract

NTT Communication Science Laboratories (CS Labs) celebrated its 30th anniversary in 2021. From the beginning, we have been engaged in research to construct basic theories that address the essence of human and information sciences and develop innovative technologies that can bring about changes in society. We aim to achieve communication that "reaches the heart" between humans and between humans and computers. In this article, I present the recent research results at CS Labs and efforts toward future advances.

Keywords: communication science, artificial intelligence, brain science

1. Introduction

NTT Communication Science Laboratories (CS Labs) was established on July 4, 1991, at Keihanna Science City, Kyoto. CS Labs, which was initially housed within the Advanced Telecommunications Research Institute International (ATR) and started from two research groups on machine learning and information theory, currently has about 150 researchers at Keihanna and Atsugi, Kanagawa Prefecture. Along with last year's open house, we set up a website to commemorate the 30th anniversary of our founding and summarize our main research results [1].

Research themes at CS Labs, which began with the mission of understanding human-to-human communication, have been developed in the two areas. The first is *approaching and surpassing human abilities* including media-information processing enabling computers to have the same abilities as humans, i.e., seeing, listening, and speaking, as well as quantum information theory and machine learning. The second area is *deeply understanding humans* including human information science for revealing various human perception and motor skills and brain science focusing on cognitive flexibility and diversity for elucidating excellent cognitive ability such as those of top athletes (**Fig. 1**).

Although these research areas have developed and changed to reflect the technological progress and social needs of each era over 30 years, we have continued to develop technologies that are close to people and society while adhering to the philosophy of *understanding the essence of communication*. I present our recent research results in the following areas.

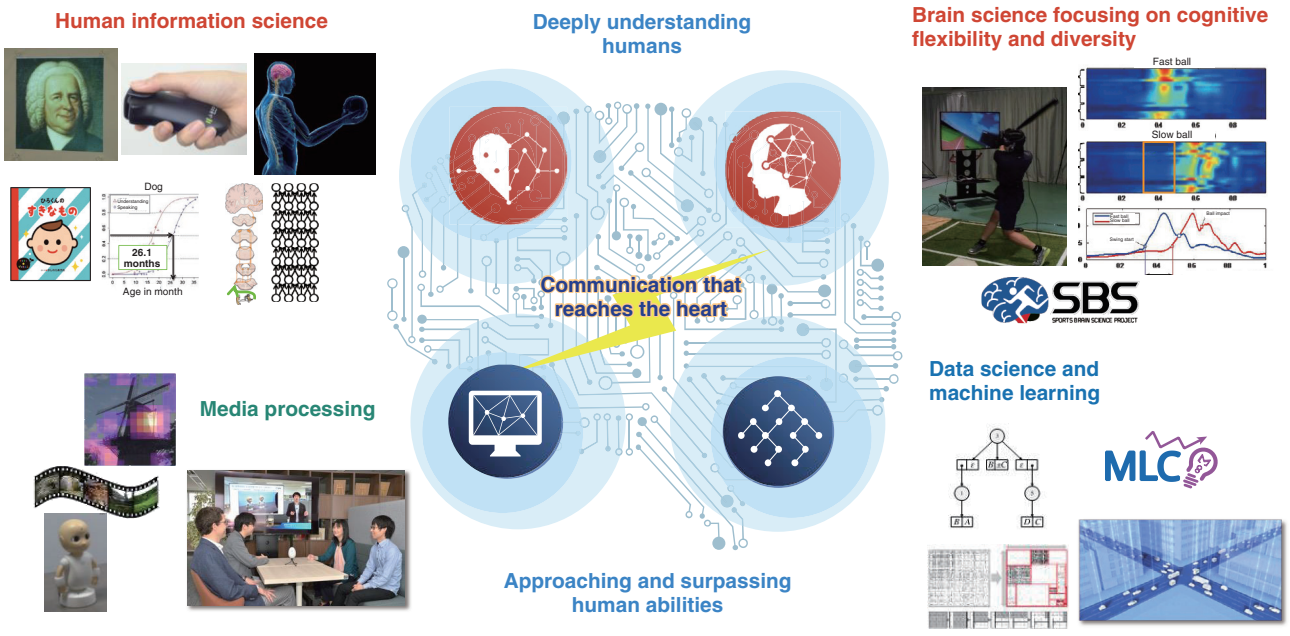

Fig. 1. Research areas of CS Labs.

2. Technologies that approach and surpass human abilities

With the advent of deep learning, artificial intelligence (AI) technology related to media processing, such as seeing, listening, and speaking, continues to make remarkable progress, and has already exceeded human discrimination performance in, for example, image-recognition competitions. However, to obtain high performance in deep learning, a huge amount of training data consisting of pairs of input data and their correct labels is generally required.

Even if we humans can obtain only a small amount of information, we can make flexible and sophisticated inferences from experience and supplementing missing information with other information. For example, although a photograph captures three-dimensional (3D) spatial information as a 2D image, humans can infer to some extent 3D information such as the shape and depth of the subject just by looking at the photograph based on experience.

Conventionally, to make computers learn such abilities, a large amount of data including 3D information measured with a special device, such as a depth sensor or stereo camera, is needed in addition to a 2D image taken as a photograph, but this is very costly. To overcome this problem of obtaining data, we proposed the deep learning technology aperture rendering generative adversarial network [2] that takes into account the relationship between aperture and blur as an optical constraint of the camera. This technology can learn 3D information such as depth and bokeh effects from only general photographs (2D information) such as public images on the Internet, and generate new images with different blur and bokeh effects with different depths of field.

Humans also have the excellent ability of selective listening, i.e., focusing on the specific voice of a person in a multi-person talking situation, such as a party, or a noisy or reverberant environment. At CS Labs, we proposed SpeakerBeam, a technology that distinguishes the voice of the target person using only voice. In 2021, we proposed Multimodal SpeakerBeam [3], which enables selective listening from multiple clues like what humans can do by combining video information and audio. This technology achieves highly accurate speaker-voice separation when there are multiple speakers with similar voice qualities. The movement of the lips is used as the main clue, and conversely, when the image of the lips cannot be obtained, the voice is used. This research is developing into a universal sound extraction technology that can distinguish not only voice but also notable sounds such as sirens of fire engines and the barking of dogs. The Feature Articles in this issue introduce the latest speech enhancement technology

for extracting high-quality voice as if it was recorded with a microphone near the speaker from the voice recorded with a microphone located at a remote location [4].

Since the 1990s, CS Labs has been researching dialogue systems that can naturally communicate with people. We initially focused on researching dialogue systems for specific purposes such as reservations and searches, but we are now researching chat-dialogue systems that can respond naturally while handling a wide range of topics regardless of purpose [5]. In 2021, with the cooperation of Seika Town Hall in Kyoto Prefecture, where the Keihanna CS Lab is located, we started an AI demonstration experiment [6] in which visitors can enjoy chat dialogue while performing operations such as government office guidance and providing tourist information. We have also released the largest *Transformer* dialogue model in Japanese, which combines ultra-large-scale dialogue data collected on the web and deep learning techniques [7]. We have been building a more cohesive dialogue system by discussing image scenes seen from the window of a vehicle where the situation of the place changes from moment to moment along with the user. We are also engaged in research for constructing a system that can memorize the preferences of the user, maintain the consistency of the dialogue content, and continue dialogue closer to humans.

There has also been progress in the field of machine learning in terms of being close to people. For example, when making decisions for people such as loan approval and recruitment, conventional machine learning techniques that simply prioritize prediction accuracy can result in unfair predictions when using a variety of subtle human characteristics, such as gender, race, and disability. We proposed a machine learning method that is based on causal relationships [8] for achieving fair accurate prediction for each individual by modeling prior knowledge about unfairness as a causal relationship (causal graph) between features and prediction results.

This issue introduces, as a cutting-edge achievement of machine learning, CS Labs' distributed deep learning technology for achieving signal-free mobility using digital twins with an eye on a future autonomous driving society [9]. This optimization technology improves the average moving speed of all vehicles while preventing them from colliding through communicating and coordinating with one another in a road network without traffic lights.

3. Research to deeply understand humans

At CS Labs, we have been studying various illusions caused by the latent functions of the brain in exploring the mechanisms of human perception and movement. We have also published a website called *Illusion Forum* [10] where one can experience various visual and auditory illusions. We obtained results that clarify the various latent functions of the brain from conducting an illusion-presentation experiment using virtual reality, indicating, for example, that a batter feels as if the ball is rising when the pitcher's pitching motion becomes faster even if the ball trajectories and ball speeds are exactly the same.

In October 2021, we started joint research with Shizuoka General Hospital on voice and language recognition for cochlear implant wearers [11]. It is known that even deaf children can acquire the same level of spoken language as children with normal hearing by wearing cochlear implants at an early stage, but the mechanism of speech perception and language development in the brain remains unclear. By approaching this issue from both medicine and brain science, we are attempting to elucidate aspects of the hearing mechanism of the elderly and other hearing-impaired people as well as the mechanisms behind individual differences in speech perception and language development.

From research on language acquisition, CS Labs published a word-familiarity database that evaluated the degree of familiarity of about 80,000 Japanese words on a 7-point scale in 1999. In 2021, we built the Reiwa version [12] for re-examining the original and includes more than 160,000 additional words. The database is commercially provided by NTT Printing Corporation. We also developed a method for estimating a person's approximate size of vocabulary by answering whether the person knows 50 selected words using this word-familiarity database. The website is open to the public [13].

4. Toward the creation of technologies that bring harmony and symbiosis among people, society, and the environment

Research activities at CS Labs have been carried out by pursuing each area of expertise, but the amount of research that crosses two or more such areas has been increasing. For example, media-processing research that specializes in a single modality such as seeing or listening has evolved into *cross-modal* information processing that handles multiple media

at the same time, such as speaker identification using sound and video, as described above. In human science as well, research is shifting to elucidating the mechanism of multisensory integration. In 2021, the *pitcher simulator*, which is the result of research that brought together all the knowledge and techniques of brain science, human science, and media processing at CS Labs, contributed to winning the gold medal of the Japan Women's Softball National Team at the major international sporting event held in Tokyo and was featured as a "secret weapon" [14] in newspapers and television. As another example, this issue presents an approach to personal cardiac modeling that combines mobile sensing, media processing, and machine learning [15].

Recent advances in science and technology and their commoditization are accelerating rapidly. Furthermore, the COVID-19 pandemic, global climate change, increasing natural disasters, and international conflict have dramatically changed our daily lives and values. There is a limit to solving increasingly complex and diversified social issues simply by pursuing research within an area of expertise, and research that creates new value through synergies with research results in peripheral areas and research in different areas is becoming increasingly important to open up new interdisciplinary research areas.

Basic research also requires a research approach from a long-term perspective that is fundamentally different from the past. Therefore, the Institute for Fundamental Mathematics was established in October 2021 to study the fundamental theory of modern mathematics at CS Labs [16]. For more information on our research at the Institute for Fundamental Mathematics, please see the article in this issue [17]. Toward the implementation of IOWN (the Innovative Optical and Wireless Network), while making full use of the latest mathematical methods, we will tackle and solve problems that occur in various areas and continue to work on communication science research to develop technologies that bring harmony and symbiosis among people having diverse values, society, and the environment.

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Futoshi Naya
Vice President and Head of NTT Communication Science Laboratories.

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

AI Hears Your Voice as if It Were Right Next to You—Audio Processing Framework for Separating Distant Sounds with Close-microphone Quality

Tomohiro Nakatani, Rintaro Ikeshita, Naoyuki Kamo, Keisuke Kinoshita, Shoko Araki, and Hiroshi Sawada

Abstract

When we capture speech using microphones far from a speaker (distant microphones), reverberation, voices from other speakers, and background noise become mixed. Thus, the speech becomes less intelligible, and the performance of automatic speech recognition deteriorates. In this article, we introduce the latest speech-enhancement technology for extracting high-quality speech as if it were recorded using a microphone right next to the speaker (close microphone) from the sound captured using multiple distant microphones. We discuss a unified model that enables dereverberation, source separation, and denoising in an overall optimal form, switch mechanism that enables high-quality processing with a small number of microphones, and their integration with deep learning-based speech enhancement (e.g., SpeakerBeam).

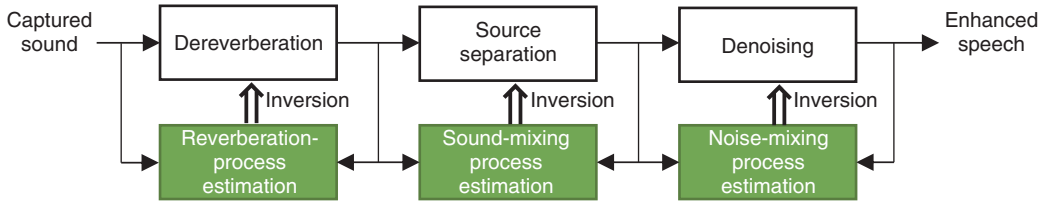
Keywords: speech enhancement, microphone array, far-field speech recording

1. Introduction

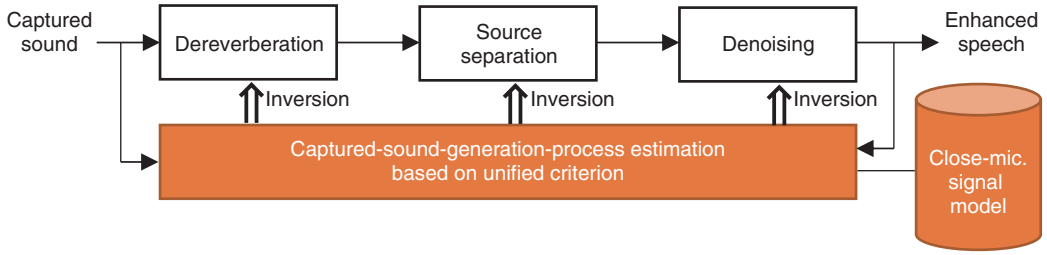
High-quality speech applications using a microphone placed near the speaker's mouth (close microphone) have been widely used, such as automatic speech recognition (ASR) using a smartphone and remote conferencing using a headset. For artificial intelligence (AI) to become a more practical assistant in our daily lives, it is required to handle speech in the same manner even when the speech is captured using microphones far from the speaker (distant microphones). However, with distant microphones, reverberation reflected from the walls or ceilings, voices from other speakers, and background noise become mixed. Therefore, the quality of the captured speech deteriorates significantly, and the performance of speech applications, such as ASR, greatly degrades. To solve this problem, we are developing speech-enhancement technology for extracting a high-quality voice of each speaker as if it were captured with a close microphone from sound captured with distant microphones. This article introduces the latest technology for multi-microphone speech enhancement that uses multiple microphones for achieving higher quality processing than with a single microphone.

2. Challenges for achieving close-microphone quality

To extract a speech with close-microphone quality from sound captured using distant microphones, it is necessary to achieve three types of processing:



(a) Conventional multi-microphone speech enhancement



(b) Unified model-based multi-microphone speech enhancement

Fig. 1. Conventional and unified model-based methods for multi-microphone speech enhancement.

dereverberation, source separation, and denoising. Dereverberation transforms a blurry speech with a distant impression into a clear speech with the impression of being right next to the microphone. When multiple speakers' voices and background noise are mixed, they are separated into individual sounds by source separation and denoising. This makes it possible to extract each speaker's voice with close-microphone quality.

Conventional multi-microphone speech-enhancement methods achieve dereverberation, source separation, and denoising by estimating the generation processes of captured sound, in which sounds propagate from the sources to the microphones and mix, then applying the inverse of the estimated processes to the captured sound (**Fig. 1(a)**). Specifically, the processes of reverberation reflecting from walls or ceilings and reaching the microphones, multiple sounds coming from different directions and mixing, and noise coming from all directions and mixing are estimated, then their inversions are applied.

For example, WPE (weighted prediction error) [1] developed by NTT is the world's first dereverberation method. It can achieve almost perfect dereverberation by estimating the reverberation process of the captured sound without any prior knowledge on what environments in which the sound was captured (i.e., by blind processing), provided the captured sound does not contain noise. Independent component analysis [2, 3], which has been actively studied worldwide by researchers, including NTT, can achieve precise source separation by blind processing, provided the captured sound does not contain reverberation.

However, these conventional multi-microphone speech-enhancement methods cannot be used to solve the three problems (reverberation, multiple sound sources, and noise) at the same time in an overall optimal form. It is impossible to simultaneously estimate all generation processes from the captured sound, which is a mixture of noise, reverberation, and multiple sounds, and execute the inversion of the entire process. Therefore, we have to apply each process in turn. For example, dereverberation is executed first assuming that noise is absent, so precise dereverberation is impossible. We then apply sound-source separation and denoising, assuming that reverberation is wholly suppressed; thus, the best performance cannot be achieved. It is therefore impossible to achieve overall optimal speech enhancement when combining these conventional methods.

The sound captured using distant microphones almost always contains reverberation, multiple sound sources, and noise. For this reason, it has been considered critical to optimally apply the three types of processing, dereverberation, source separation, and

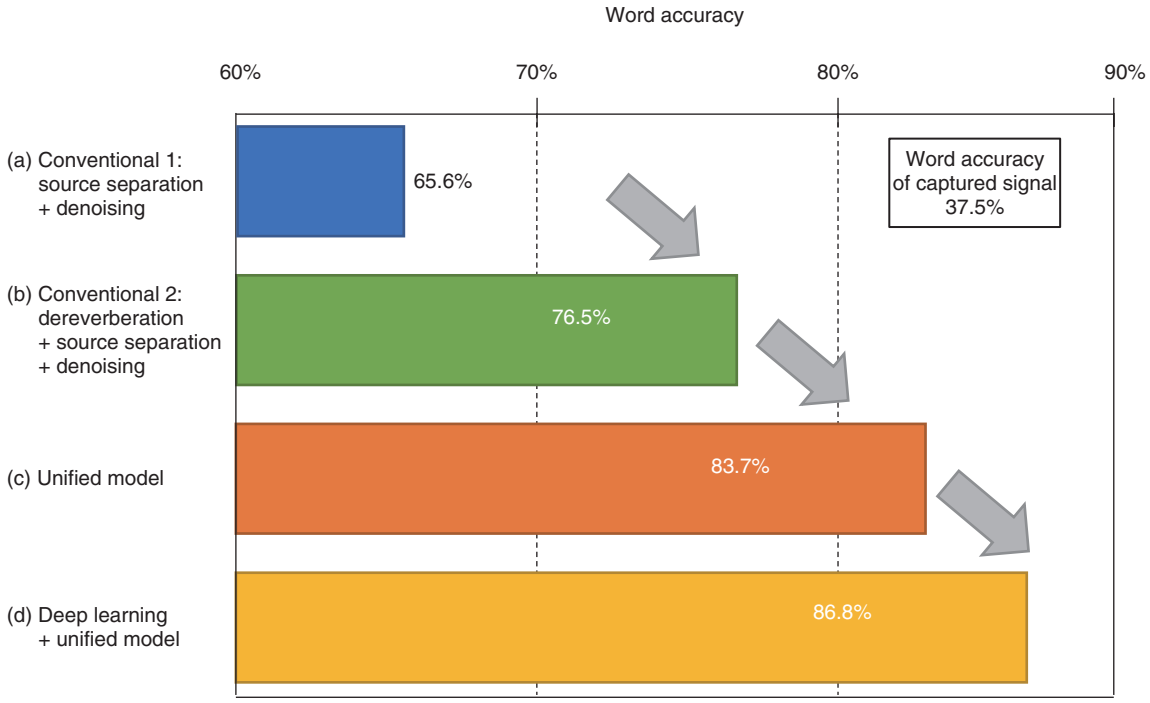


Fig. 2. Improvement in ASR performance using multi-microphone speech enhancement.

denoising, in an overall optimal form.

3. Unified model for dereverberation, source separation, and denoising

In response to this, we devised a unified model that can solve the three problems in an overall optimal form [4, 5]. The unified model first mathematically models the general properties that close-microphone quality speech and noise must satisfy. It can then enable overall optimum processing by optimizing each type of processing on the basis of the *unified criterion* that the sound obtained from combining the three types of processing best satisfies the close-microphone property (**Fig. 1(b)**). For example, we can significantly improve ASR using distant microphones with the unified model (**Figs. 2(a)–(c)**).

Figure 3 shows a spectrogram of two speech signals and noise captured using a close microphone and the mixture of them captured using a distant microphone. The speech signals captured using the close microphone are sparse signals in which the sound concentrates in separate local areas, and are non-stationary signals that change with time. In contrast, noise is a dense and stationary signal in which the sound spreads over a wider area and does not change much with time. However, the mixture captured using a distant microphone has different characteristics. It is denser than the speech signals with close-microphone quality and more non-stationary than noise with close-microphone quality.

The unified model uses the differences in these sound characteristics. It controls dereverberation, source separation, and denoising so that the sound resulting from their application best satisfies the characteristics of speech and noise with close-microphone quality. For example, in dereverberation, we estimate the reverberation-generation process and apply its inversion so that the sound obtained in combination with source separation and denoising best satisfies the close-microphone quality. Similarly, we optimize source separation and denoising by estimating the sound-generation process and applying its inversion to best satisfy the close-microphone quality when combined with dereverberation. With the aim of achieving close-microphone quality, it has become possible to execute overall optimum processing when combining all types of processing.

We have also developed computationally efficient algorithms for unified model-based multiple microphone speech enhancement [6, 7]. For example, the processing using the unified model illustrated in

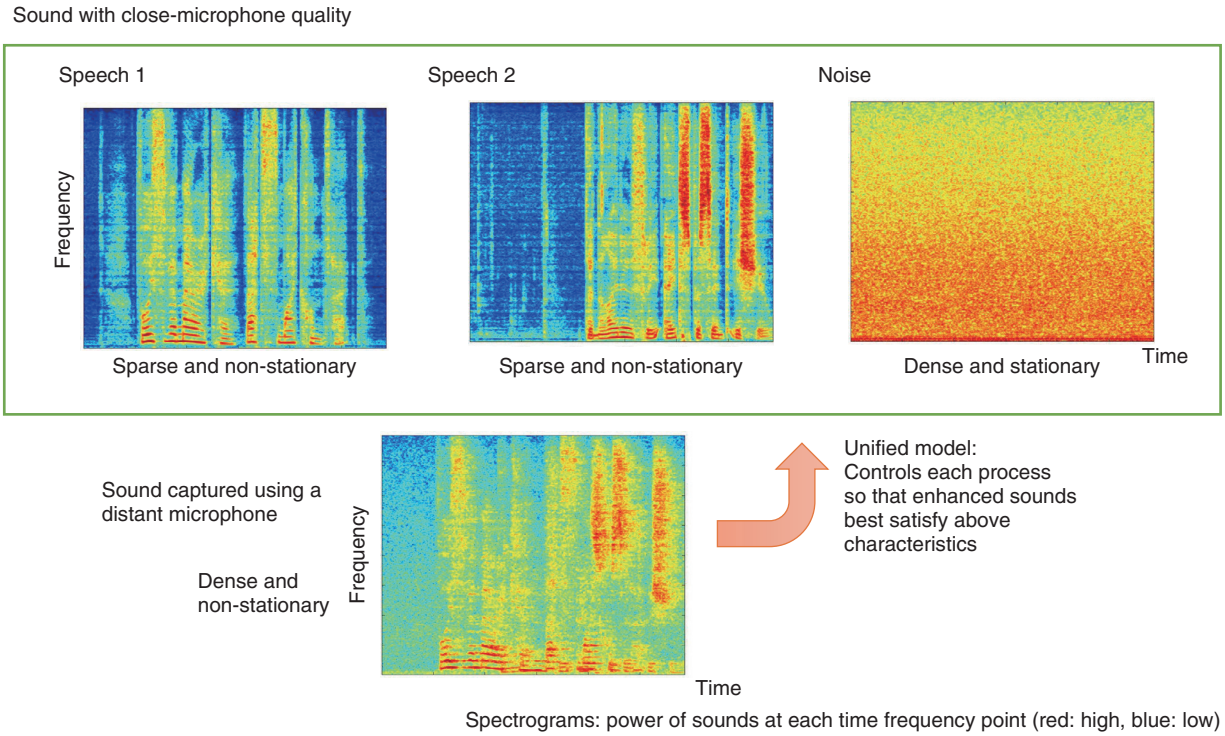


Fig. 3. Spectrograms of sounds captured using close and distant microphones.

Fig. 2 (executing overall optimization of dereverberation, source separation, and denoising using eight microphones) can now be completed in real time using a Linux computer. When we limit the problem to extracting a speaker's voice by blind processing from background noise and little reverberation, we can reduce the computational cost to the extent that real-time processing is possible even with an embedded device.

4. Switch mechanism enabling accurate estimation with a smaller number of microphones

A switch mechanism is an applied technology using the unified model and enables highly accurate estimation even with a relatively small number of microphones [8, 9]. With conventional multi-microphone speech-enhancement methods, it is necessary to use a sufficiently large number of microphones for precise processing compared with the number of sound sources included in the captured sound. This hinders the application of multi-microphone speech enhancement to real-life problems. To solve this problem, we introduce a switch mechanism that can improve estimation accuracy with a small number of microphones.

The idea of this switch mechanism is summarized as follows. Even when the captured sound contains many sound sources, the number of sources appearing simultaneously can be smaller when counting them within each short time interval. Let us explain this using **Fig. 4**. The horizontal axis is time, and a horizontal bar in each color represents when each of the three speakers speaks. When we divide the horizontal axis into short intervals a, b, and c, as shown in the figure, only two speakers are speaking in each time interval even though there are three speakers in total. With this interval division, we can improve multi-microphone speech enhancement by applying it separately to each short interval with the decreased number of speakers. We call this a switching mechanism because we switch speech enhancement for each short interval.

When combined with the unified model, the switch mechanism can perform best. We can use the unified model to optimize the interval-wise application of speech enhancement and the switch mechanism's time interval division. This unified model-based speech enhancement can optimize the all processing

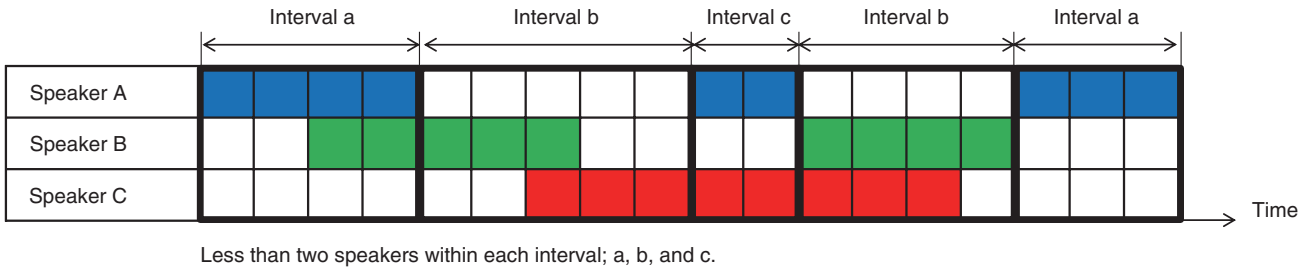


Fig. 4. An example of each speaker's utterance periods in a conversation among three speakers.

types (dereverberation, source separation, and denoising) with the switch mechanism so that the enhanced speech best satisfies the close-microphone quality.

5. Unified model as a versatile technique of audio-signal processing

As described above, our unified model provides theoretically and practically excellent guidelines for integrating the three processing types in speech enhancement that we have conventionally combined in more heuristic ways. The unified model can provide a mechanism to achieve overall optimization even when combining more complicated processing approaches such as the switch mechanism. We can use the unified model as a versatile technique providing a basis for future audio-signal processing-technology development.

6. Future direction: optimal integration with deep learning

Deep learning is another fundamental approach to speech enhancement, and its integration with multi-microphone speech-enhancement methods is vital for the future development. While deep learning can conduct processing that is difficult with multi-microphone speech enhancement, such as voice characteristics-based selective listening using SpeakerBeam, a deep learning-based approach for computational selective hearing based on the characteristics of the target speaker's voice [10], it also has severe limitations. For example, with deep learning-based speech enhancement, improvement in ASR performance is minimal, and sound quality largely degrades due to reverberation. Therefore, both deep learning and multi-microphone speech-enhancement methods complement each other, thus are indispensable. For example, even when the ASR performance or quality of enhanced speech does not much improve solely by deep learning-based speech enhancement, they can be improved when combined with the multi-microphone speech enhancement. **Figure 2(d)** shows that the combined approach further improves ASR performance compared with solely using the unified model-based multi-microphone speech enhancement. Speech enhancement will have much higher functionality and quality through developing an optimal integration method for both deep learning and multi-microphone speech enhancement.

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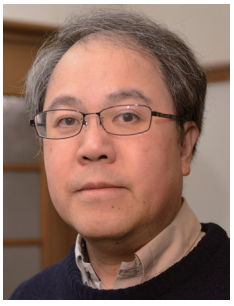
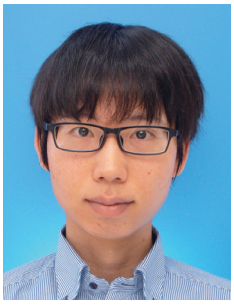


Tomohiro Nakatani
Senior Distinguished Researcher, Signal Processing Research Group, Media Information Laboratory, NTT Communication Science Laboratories.
He received a B.E., M.E., and Ph.D. from Kyoto University in 1989, 1991, and 2002. Since joining NTT as a researcher in 1991, he has been investigating speech-enhancement technologies for developing intelligent human-machine interfaces. He was a visiting scholar at Georgia Institute of Technology in 2005 and visiting assistant professor in the Department of Media Science, Nagoya University, Aichi from 2008 to 2018. He received the 2005 Institute of Electronics, Information and Communication Engineers (IEICE) Best Paper Award, the 2009 Acoustical Society of Japan (ASJ) Technical Development Award, the 2012 Japan Audio Society Award, the 2015 Institute of Electrical and Electronics Engineers (IEEE) Automatic Speech Recognition and Understanding Workshop (ASRU) Best Paper Award Honorable Mention, the 2017 Maejima Hisoka Award, and the 2018 International Workshop on Acoustic Echo and Noise Control (IWAENC) Best Paper Award. He was a member of the IEEE Signal Processing Society Audio and Acoustic Signal Processing Technical Committee (AASP-TC) from 2009 to 2014 and served as the chair of the AASP-TC Review Subcommittee from 2013 to 2014. He was a member of the IEEE Signal Processing Society Speech and Language Processing Technical Committee (SLTC) from 2016 to 2021. He served as an associate editor of the IEEE Transactions on Audio, Speech and Language Processing from 2008 to 2010, chair of the IEEE Kansai Section Technical Program Committee from 2011 to 2012, technical program co-chair of IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA) 2007, workshop co-chair of the 2014 REVERB Challenge Workshop, general co-chair of the 2017 IEEE ASRU Workshop, and chair of IEEE Signal Processing Society Kansai Chapter from 2019 to 2020. He is an IEEE Fellow, and a member of IEICE and ASJ.

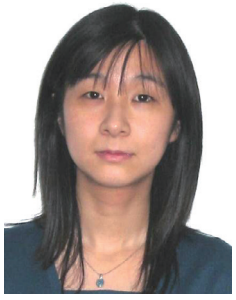


Rintaro Ikeshita
Researcher, Signal Processing Research Group, Media Information Laboratory, NTT Communication Science Laboratories.
He received a B.E. and M.S. from the University of Tokyo in 2013 and 2015 and joined NTT in 2018. He received the 17th Itakura Prize Innovative Young Researcher Award from ASJ in 2022 and the 49th Awaya Prize Young Researcher Award from ASJ in 2021. He is a member of IEEE and ASJ.

Naoyuki Kamo
Researcher, Signal Processing Research Group, Media Information Laboratory, NTT Communication Science Laboratories.
He received a B.S. and M.S. from Kyoto University in 2012 and 2014. Before he joined NTT in 2020, he developed as a contributor the well-known deep learning-based open software tools for speech-signal processing ESPNET-1 and 2. Since joining NTT, he has developed neural network-based techniques, such as speech enhancement and intelligibility prediction. He is a member of ASJ.

Keisuke Kinoshita
Research Scientist, Google Japan.

He received an M. Eng. and Ph.D. from Sophia University, Tokyo, in 2003 and 2010. After joining NTT Communication Science Labs in 2003, he was engaged in fundamental research on various types of speech, audio, and music-signal processing, including 1ch/multi-channel speech enhancement (blind dereverberation, source separation, noise reduction), speaker diarization, robust speech recognition, and distributed microphone-array processing, and developed several types of innovative commercial software. He has been in his current position since October 2022. He has been serving as an associate editor of IEEE/ACM Transactions on Audio, Speech and Language Processing since 2021 and member of IEEE AASP-TC since 2019. He also served as the chief coordinator of the REVERB Challenge (2014), an editor of IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences (from 2013 to 2017), and guest editor of EURASIP journal on advances in signal processing (2015). He was honored to receive the 2006 IEICE Paper Award, the 2010 ASJ Outstanding Technical Development Prize, the 2011 ASJ Awaya Prize, the 2012 Japan Audio Society Award, 2015 IEEE-ASRU Best Paper Award Honorable Mention, and 2017 Maejima Hisoka Award. He is a member of IEEE and ASJ.



Shoko Araki
Group Leader and Senior Research Scientist, Signal Processing Research Group, Media Information Laboratory, NTT Communication Science Laboratories.

She received a B.E. and M.E. from the University of Tokyo in 1998 and 2000 and Ph.D. from Hokkaido University in 2007. Since she joined NTT in 2000, she has been engaged in research on acoustic-signal processing, array-signal processing, blind-source separation, meeting diarization, and auditory scene analysis. She was a member of the IEEE Signal Processing Society AASP-TC (2014–2019) and currently serves as its vice chair. She has been a board member of ASJ since 2017 and currently serves as vice president of ASJ (2021–2022). She also served as a member of the organizing committee of International Symposium on Independent Component Analysis and Blind Signal Separation (ICA) 2003, IWAENC 2003, IEEE WASPAA 2007, Hands-free Speech Communications and Microphone Arrays (HSCMA) 2017, IEEE WASPAA 2017, IWAENC 2018, IEEE WASPAA 2021 and the evaluation co-chair of the Signal Separation Evaluation Campaign (SiSEC) 2008, 2010, and 2011. She received the 19th Awaya Prize from ASJ in 2001, the Best Paper Award of the IWAENC in 2003, the TELECOM System Technology Award from the Telecommunications Advancement Foundation in 2004 and 2014, the Academic Encouraging Prize from IEICE in 2006, the Itakura Prize Innovative Young Researcher Award from ASJ in 2008, the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology, The Young Scientists' Prize in 2014, IEEE Signal Processing Society Best Paper Award in 2014, and IEEE ASRU 2015 Best Paper Award Honorable Mention in 2015. She is an IEEE Fellow for contributions to blind-source separation of noisy and reverberant speech signals. She is a member of IEEE, IEICE, and ASJ.

Hiroshi Sawada
Executive Manager and Senior Distinguished Researcher, Innovative Communication Laboratory, NTT Communication Science Laboratories.

He received a B.E., M.E., and Ph.D. in information science from Kyoto University in 1991, 1993, and 2001. His research interests include statistical signal processing, audio-source separation, array-signal processing, machine learning, latent variable modeling, graph-based data structures, and computer architecture. He received the Best Paper Award of the IEEE Circuit and System Society in 2000 and the Best Paper Award of IEEE Signal Processing Society in 2014. He is an IEEE Fellow and member of IEICE and ASJ.

Personal Heart Modeling Using Mobile Sensing

Kunio Kashino, Ryohei Shibue, and Shingo Tsukada

Abstract

Public expectations for healthcare in daily life using digital technologies are increasing. With this in mind, we first focused our research on biomedical informatics related to the human heart. We have been experimenting with ways to observe the acoustical and electrical signals generated by the living body and how to replicate, in a computer, the state and function of a person's heart at a particular point in time. In this article, we introduce new technologies for measuring and estimating the activity of the human heart.

Keywords: biomedical informatics, healthcare, mobile sensing

1. Personalized biomedical modeling

Even in the fields of medicine and health, the traditional limitations of physical location, time, and distance are giving way to continuous advances in sensing, communications, artificial intelligence (AI), and other information-processing technologies. An increasing number of people use wearable devices, such as smartwatches, for their personal health management. Further utilization of biometric information in daily life will enable continuous healthcare, useful not only when ill but also before and after treatment, and personalized healthcare, not just patterned treatments for diseases. Research and development and practical applications in this field is very active worldwide.

As part of NTT's Medical and Health Vision, a simulator called the Bio-Digital Twin is being developed to support risk control and improved wellness [1] by predicting future physical and mental conditions of a person. The Bio-Digital Twin is a computational model that captures a wide variety of biomedical information, from molecular and cellular scales to organs and their interconnections, even the environment in which a person lives, expressing those connections as a network. One of the components of the Bio-Digital Twin is personal heart modeling. Personal heart modeling means measuring the operation and condition of an individual's heart then mathematically and logically representing the person's heart in a computer in such a way that allows simulation under various assumptions.

Our research team aims to obtain more detailed biometric information than with conventional wearable devices such as smartwatches, while still enabling measurement in daily life without any undue burden [2].

2. New sensing

One of our prototype biometric sensing instruments is a wearable electrocardiogram (ECG) device. Electrocardiography, as commonly used in medical institutions, uses 10 electrodes placed on the arms, legs, and chest to obtain 12 potential differences. Smartwatches that obtain a simple ECG measuring the potential difference just between a person's two hands are becoming popular. In contrast, our prototype is centered on the apical region of the chest where the heart is closest to the rib cage as a reference point with opposite electrode poles in three nearly orthogonal directions to capture the electrical activity of the heart in three dimensions (**Fig. 1(a)**). In our prototype, the electrodes and wiring are integrated with a stretchable shoulder belt, making it easy to fit to any sized adult by adjusting the shoulder and waist

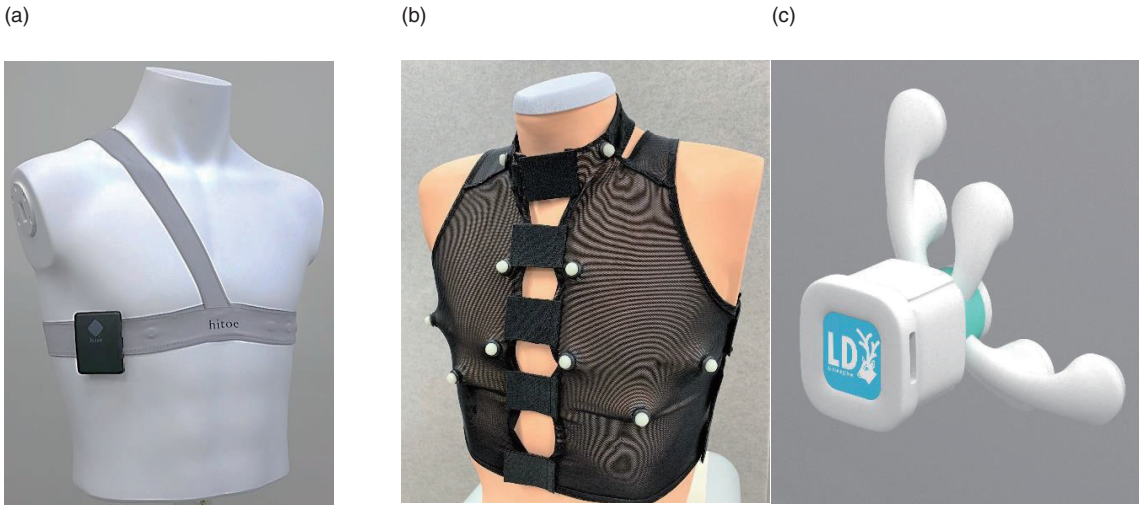


Fig. 1. Wearable ECG device (a) and AI Telestethoscopes (wearable type (b), handheld type (c)). Prototypes for research purpose.

straps [3].

Another prototype biometric sensing instrument is what we call the "AI Telestethoscope," which is capable of measuring multi-channel acoustic signals simultaneously with an ECG. We prototyped both a wearable-type (**Fig. 1(b)**) and handheld-type (**Fig. 1(c)**) AI Telestethoscope. They both enable sensed data to be transmitted in real time to a remote location where a doctor or nurse can listen to the sound coming from specific locations on the body surface by interactively selecting them on a terminal screen. Unlike conventional wireless electronic stethoscopes that use a single microphone, our AI Telestethoscopes use multiple microphones to simultaneously capture sound signals at multiple locations to capture the sounds of the heart's activity in three dimensions.

3. Information processing of signals to explore inside a living body

Information processing is key to estimating the internal state and functioning of a living body from biomedical signals measured on the surface of the body. The novel sensing instruments introduced in the previous section are designed to capture precise biometric information for personal heart modeling.

The heart works in accordance with the cyclical activity of heart muscle cells called cardiomyocytes. There are two types of cardiomyocyte activity: electrical and mechanical. An ECG generally shows the combined effects of the actions of many cardiomyocyte cells in the heart that can be observed as electrical potential differences on the body surface. On the other hand, heart sounds are mainly caused by the mechanical activity of the heart, especially the opening and closing of the four valves inside the heart. Abnormalities in the heart can also generate distinctive sounds, such as the vibrations caused by turbulent blood flow which can be heard as a so-called "heart murmur."

Both the bio-electrical and bio-acoustic signals that can be observed on the surface are the result of a mixture of many factors. It is not easy to estimate the cause backwards from the effect. That is, to understand the condition of the heart inside the body by tracing its physical mechanism in reverse from surface observations.

We are approaching this seemingly ill-posed problem by using three-dimensional (3D) electrical and acoustical information to derive 3D location clues, and by introducing various information-processing techniques such as the use of physical constraints and machine learning [4].

When testing for heart abnormalities, it is not uncommon for a typical ECG to show nothing more than irregularity in a few waveforms. To solve this problem, we attempt to visualize, from the ECG waveforms, the electrical action potential of localized groups of cardiomyocytes by estimating statistical parameters related to changes in cardiomyocyte populations (tensor ECG) [5]. Visualization of action

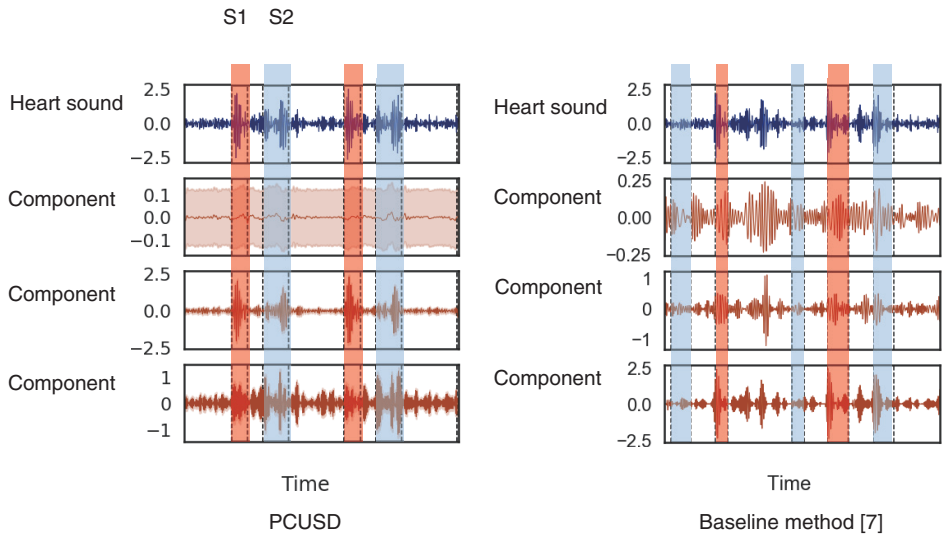


Fig. 2. Estimation of S1 and S2 segments.

potential information at various locations in the heart is expected to help with early detection of arrhythmias associated with heart failure, ischemic heart disease, and sudden cardiac death because abnormalities can be more clearly expressed than with standard ECGs.

We also expect to be able to estimate what sounds are coming from which locations in the heart by capturing heart sounds in three dimensions. The location of the sound, its tone, and its acoustic characteristics are known to be important clues for determining the presence and severity of heart disease. Historically, sounds have been captured on the surface of the body using a manual stethoscope or phonocardiograph, and there has been no better way to listen to particular sounds within the body in a non-invasive manner.

To this end, we developed a novel oscillator decomposition technique for heart sounds that can estimate internal sound sources from sounds observed on the body surface, called PCUSD (Physically Constrained Unsupervised Signal Decomposition) [6]. PCUSD focuses on the periodicity of heart movement and the mechanism of heart-sound generation. Normally, the heart moves periodically, going through four stages (cyclical phases) in sequence: S1, systolic, S2, and diastolic, where S1 corresponds to the first sound of a heartbeat and S2 corresponds to the second sound. Different heart valves open and close during each stage, and their vibrations generate heart sounds. We can assume there are multiple vibrational components to the sounds made by each valve and that their amplitudes change in accordance with the condition of the heart during the sequential phases of the cardiac cycle. This led us to construct a probabilistic generation model of the mechanisms of heart sounds based on physical modeling of the heart valves.

Table 1. S1 and S2 segment estimation accuracy of PCUSD and baseline method [7]. F1 score is an accuracy measure, the larger the better.

F1 score	PCUSD	Baseline
S1	96.1	86.5
S2	96.4	85.7

Figure 2 shows an example of applying PCUSD to a single channel of heart sound. We examined the estimation accuracy of the S1 and S2 intervals. The figure shows a case of mitral regurgitation with associated heart murmur. The presence of a heart murmur (in this case, between S1 and S2) generally makes it even more difficult to estimate the heart's condition. The right panel shows the results from a conventional method [7] that does not use a generation model. It shows that it is sometimes prone to estimation errors. In contrast, the left panel shows our PCUSD's results, indicating improved estimation accuracy for the same S1 and S2 intervals. **Table 1** shows this improvement numerically.

It is straightforward to apply PCUSD to multichannel heart sounds. **Figure 3** shows four acoustic channels (Fig. 3(a)) observed on the body surface of

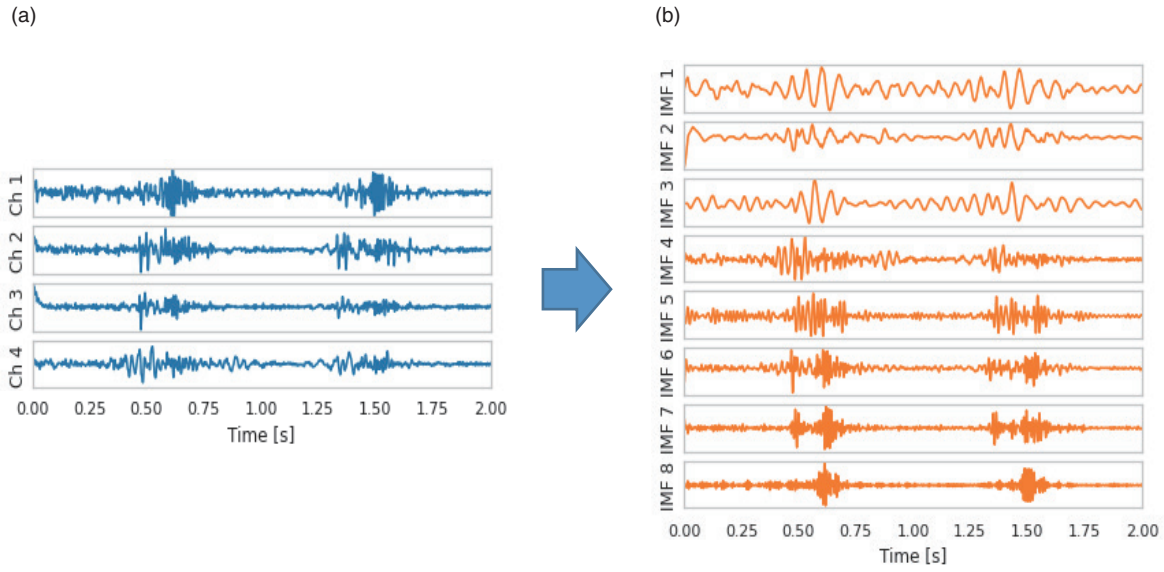


Fig. 3. Sounds captured on the body surface (a) and estimated in-body vibration waveforms (b).

a patient with aortic stenosis and eight internal sound source waveforms (Fig. 3(b)) estimated with PCUSD from the four acoustic channels. Because PCUSD uses a physical model of valve vibration, all (or almost all) these components are assumed to originate from the four valves of the heart. Each of these components can be heard as sound. AI analysis of each waveform is expected to make it possible to reliably diagnose the condition of a malfunctioning heart valve and its progressive deterioration from heart sounds—acoustic biomedical information—captured on the body surface.

4. Toward utilization

The new sensing and estimation technologies described above can potentially provide a more detailed understanding of heart activity than standard ECG and electronic stethoscope technologies currently available. Some heart abnormalities are more likely to cause electrocardiographic abnormalities and be detected using an ECG. Others are more likely to cause heart sound abnormalities and be detected through auscultation. There is yet another set of abnormalities detectable by comparison of the heart's output of electrical and acoustic signals.

We aim to actualize our vision of personal heart modeling by integrating our new technologies to estimate the condition of the heart based on real-time biomedical data capture and information processing with other relevant patient information such as their electronic health records, family medical history, recent blood tests, pre-existing medical imaging, and current public health status. This approach can potentially help people adopt a healthier lifestyle more appropriate for their personal risks of heart disease and lead to earlier detection of any heart abnormalities if they occur.

When discussing the usefulness of new technologies for medical and healthcare applications, solid research and validation is of paramount importance. Therefore, we are collaborating with multiple medical institutions, research institutions, and specialized hospitals to assess the potential of our technologies to meaningfully improve early detection of certain types of heart diseases, provide useful support for people suffering from heart failure, serve as a tool for patients and doctors during cardiac rehabilitation. Together with our collaborators, we will continue to actively verify the feasibility of this ongoing research.

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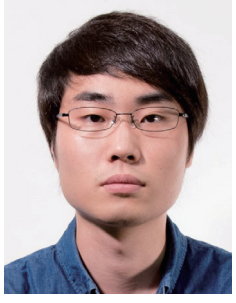
Kunio Kashino
Senior Distinguished Researcher, NTT Communication Science Laboratories and NTT Basic Research Laboratories.
He received a Ph.D. in electrical engineering from the University of Tokyo in 1995, and then joined NTT Basic Research Laboratories. He was a visiting scholar in Cambridge University in 2002. His research interests include audio and crossmodal information processing, media search, and biomedical informatics. He is a member of the Institute of Electrical and Electronics Engineers (IEEE) and the Association for Computing Machinery. He received IEEE Transactions on Multimedia Paper Award in 2004, Maejima Hisoka Award in 2010, Kenjiro Takayanagi Achievement Award in 2016, the Institute of Electronics, Information and Communication Engineers (IEICE) Achievement Award in 2017, and the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology in 2019.



Ryohei Shibue
Researcher, NTT Communication Science Laboratories and NTT Basic Research Laboratories.
He received a B.E. and M.E. in information science and technology from the University of Tokyo in 2015 and 2017. He joined NTT Communication Science Laboratories in 2017 and studied statistical modeling for eye movements. He is currently studying cardiovascular signal processing. He is a member of the Japan Statistical Society and the Japan Neuroscience Society.

Shingo Tsukada
NTT Fellow, Bio-Medical Informatics Research Center, NTT Basic Research Laboratories.
He received an M.D. from Toyama Medical and Pharmaceutical University and his medical license in 1990. He also received a Ph.D. in medicine from University of Tsukuba in 2003. He was a visiting researcher at the University of California San Diego, USA, from 2003 to 2005. He joined NTT Basic Research Laboratories in 2010 as a research specialist and became a senior research scientist in 2013. Since then, he has been engaged in the study of mechanism and activity control of signal transduction of brain cells. His current interests are the detection of biomedical signals using novel wearable-type and implant-type bioelectrodes based on the composites of conductive polymers with various fibers and textiles. He was designated as a fellow of NTT in 2018. He is a member of Society for Neuroscience, the Physiological Society of Japan, the Japan Society of Applied Physics, the Japan Neuroscience Society, the Japanese Circulation Society, and the Japanese Orthopedic Association.

Smart Traffic Coordination via Learnable Digital Twins—Future Possibilities of Distributed Deep Learning

Kenta Niwa

Abstract

Instead of controlling individual systems (Internet of Things (IoT) devices, smartphones, servers, etc.), which is the current mainstream, NTT Communication Science Laboratories aims to coordinate and control an overall system consisting of a set of IoT devices via digital twins. I report on the latest research projects regarding optimal coordination of overall IoT devices using collective intelligence in digital twins, i.e., (i) traffic coordination of autonomous vehicles and (ii) federated learning on datacenter networks.

Keywords: digital twin computing, traffic coordination, distributed learning

1. Introduction

It has become commonplace to use advanced machine learning technology via e.g., voice commands on smartphones. The future of the machine learning field will be learning collective intelligence for efficient use of individual systems (Internet of Things (IoT) devices, smartphones, servers, etc.). I believe that a possible innovation in this field will be optimal coordination and control of an overall system consisting of many IoT devices, e.g., autonomous vehicles on traffic networks, servers on datacenter networks, and power plants on energy networks. In this article, I introduce two research projects regarding collective intelligence learning via digital twins.

2. Signal-free mobility project

Future information and communication technology is expected to enable an advanced mobility society in which people, vehicles, and infrastructure cooperate with each other to provide further safety and efficiency. In the Innovative Optical and Wireless Network (IOWN), *signal-free mobility* is presented as a concept of this advanced mobility society. As shown in **Fig. 1**, vehicles autonomously travel streets with no traffic signals while communicating with each other to shorten the time to reach destinations without collisions. As the first step in achieving signal-free mobility, NTT Communication Science Laboratories is tackling the problem of traffic coordination in a distributed manner [1].

Signal-free mobility aims to predict optimal vehicle states to shorten travel time without collisions via feedback between digital twins and real vehicles. To achieve optimal coordination and control of a huge number of vehicles in real time, state transition should be distributed, i.e., by alternatingly repeating computation in each vehicle and communication among vehicles. Therefore, the main research topic is to formulate learnable digital twins to predict the optimal states of a complex overall system in a distributed manner. Digital twins can be modeled using a graph composed of vehicles (nodes shown as yellow vertices) and their connections (edges shown in green connection lines), as shown in **Fig. 2**. Although

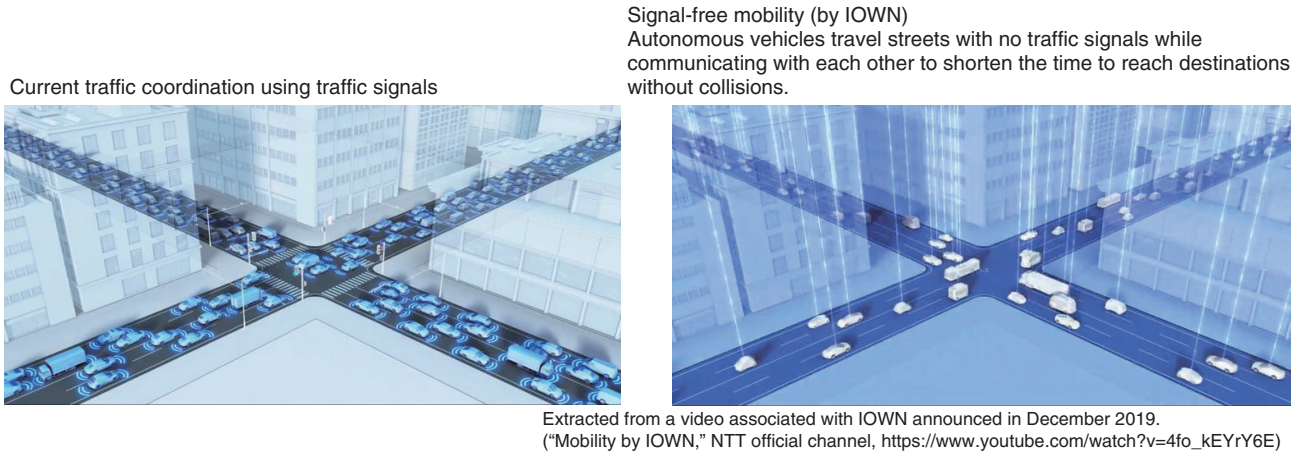


Fig. 1. Concept of signal-free mobility.

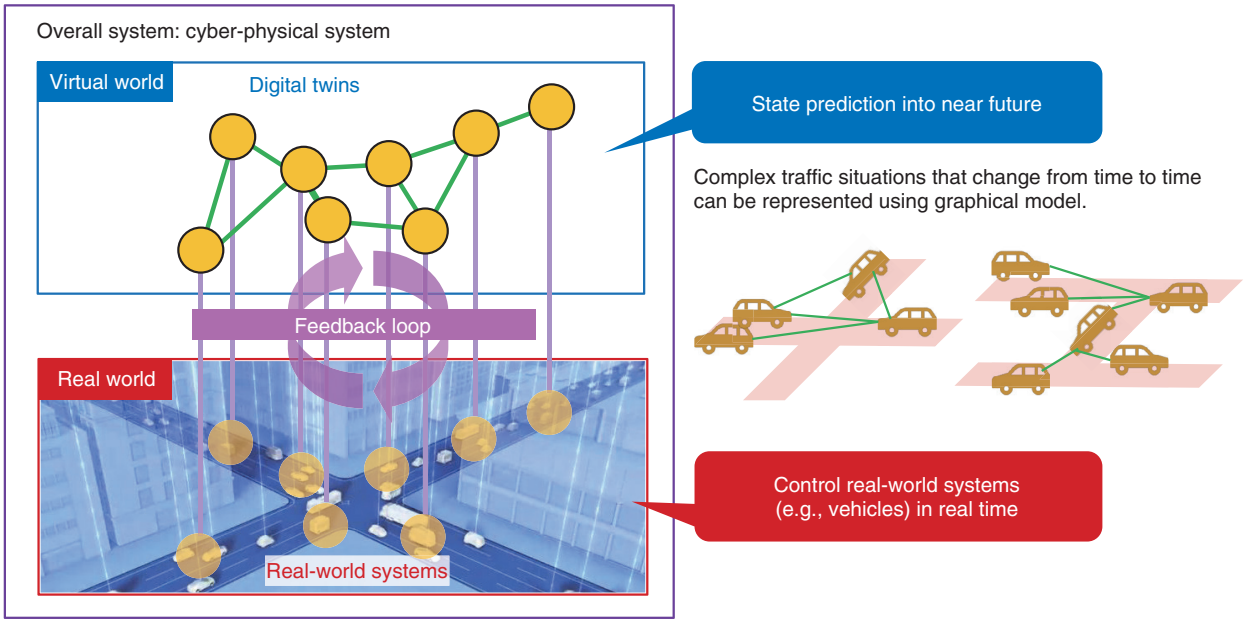


Fig. 2. Graphical modeling of digital twins for traffic coordination, which alternatingly repeats state prediction into the near future and controls real vehicles in real time.

overall traffic is a very complex system that changes from time to time, this graphical model can represent traffic as a combination of simple components, i.e., local state prediction of each vehicle and communication among neighboring vehicles.

Computation procedures on digital twins for traffic coordination is illustrated in **Fig. 3**. In forward propagation (Fig. 3(a), left to right), time evolution of both optimal state transition on digital twins and feedback control of real vehicles is illustrated. This is composed of alternating the repeating of multiple steps, i.e., observation-data collection (e.g., image sets of surrounding travel/road situations), calculation of local vehicle state and repulsive force to maintain more than a certain distance between vehicles, and information exchange through communications among neighboring vehicles. To enable real-time traffic coordination, a vehicle's state calculation can be

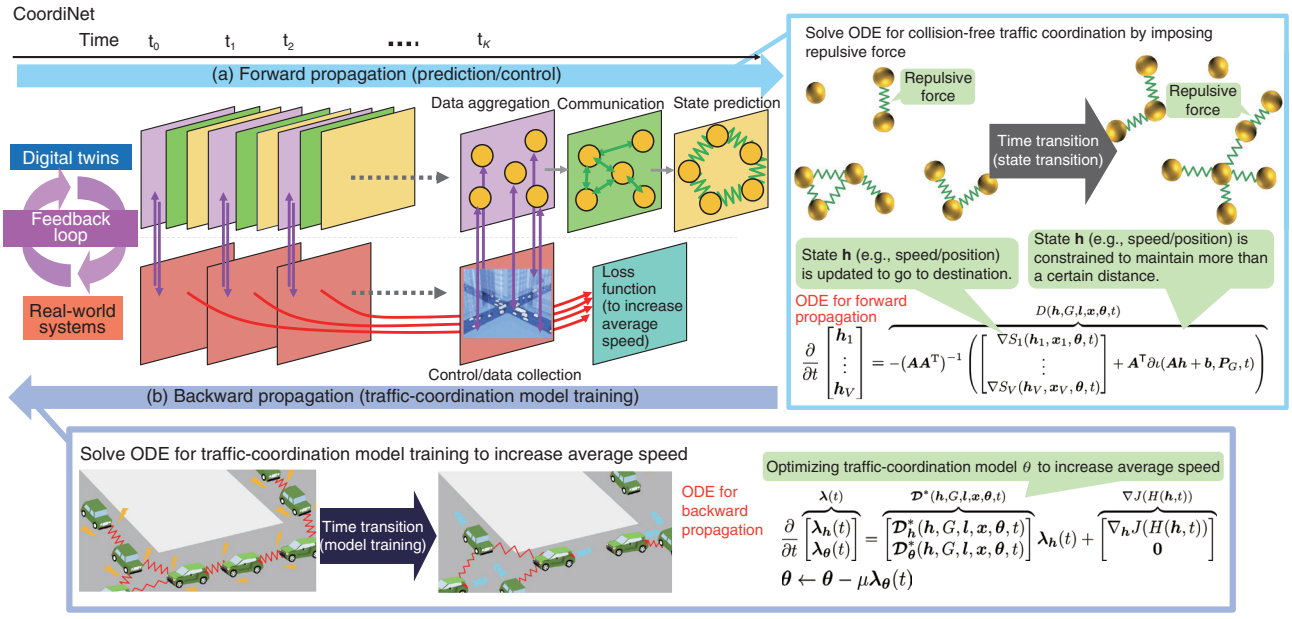


Fig. 3. CoordiNet that represents time-series processing for traffic coordination via digital twins. (a) Forward propagation (from left to right): Optimal states of vehicles can be predicted through feedback between digital twins and real vehicles. (b) Backward propagation (from right to left): Model parameters in state transition model are sequentially optimized for efficient traffic coordination.

carried out in a decentralized manner. In backward propagation (Fig. 3(b), right to left), learnable model parameters in the state-transition model are sequentially updated for efficient traffic coordination by increasing the average speed. These two flows (forward and backward propagations) were first expressed using continuous ordinary differential equations (ODEs)[*1], the spatially and temporally discretization of which resulted in a special neural network architecture (CoordiNet), as shown in Fig. 3.

With CoordiNet, a signal-free mobility system can be constructed, which is composed of prediction/control and model-training phases, as shown in **Fig. 4**. In the model-training phase, a number of traffic simulations on digital twins are executed. In these simulations, data collection assuming various traffic situations is conducted by varying the number of vehicles and their initial positions and traveling not only on actual roads but also on those created in virtual worlds. The model parameters for state transition are sequentially updated to increase the vehicle's average speed. Through training via a number of traffic simulations, the trained model is expected to be robust to unexpected road situations. Since this model-training phase is computationally heavy, model update is assumed to be executed in non-real-time (after several hours to one day). The prediction/control phase deploys a pre-trained model for real-world traffic coordination. In the constructed system, each feedback loop between digital twins and real vehicles is conducted in real time (in about 0.1–0.4 s).

Some of the results from the above traffic simulations for the model-training phase are shown in **Fig. 5**. It was found that the average speed increased as the traffic simulation was repeated with CoordiNet. When the speed is normalized to set its maximum value to 1.0, the average speed was increased up to 0.90 after training compared with 0.64 before training using randomly initialized hyper-parameters. This result indicates that data collection via traffic simulations is efficient for learning a traffic-coordination model. I also examined the performance of a conventional neural network (graph attention network (GAT)[*2]) that does not strictly restrict vehicle

*1 ODE: Continuous physical phenomena such as fluids and weather are often represented by ODEs. In this report, complex phenomena in traffic coordination are represented using an ODE such that real-world systems and digital twins can interact with each other.

*2 GAT: A graph neural network that updates state variables while adaptively updating the weights between connected nodes. Note that GAT has not been proposed for application to traffic coordination.

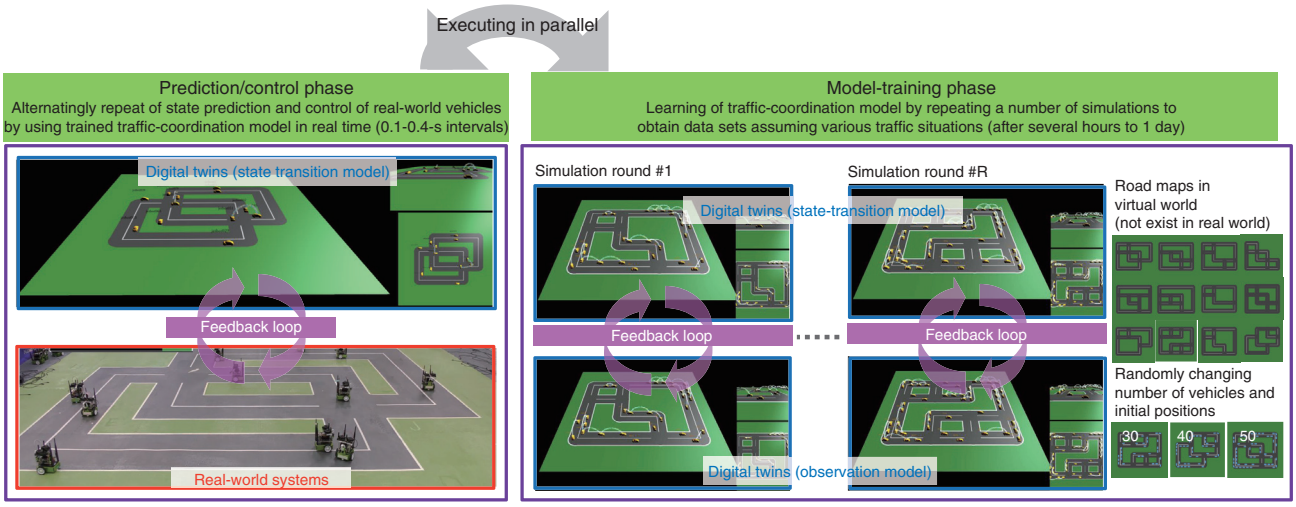
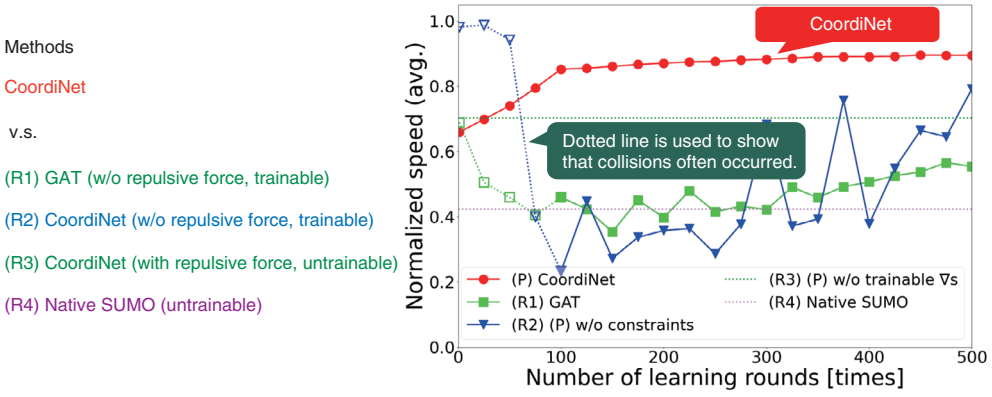
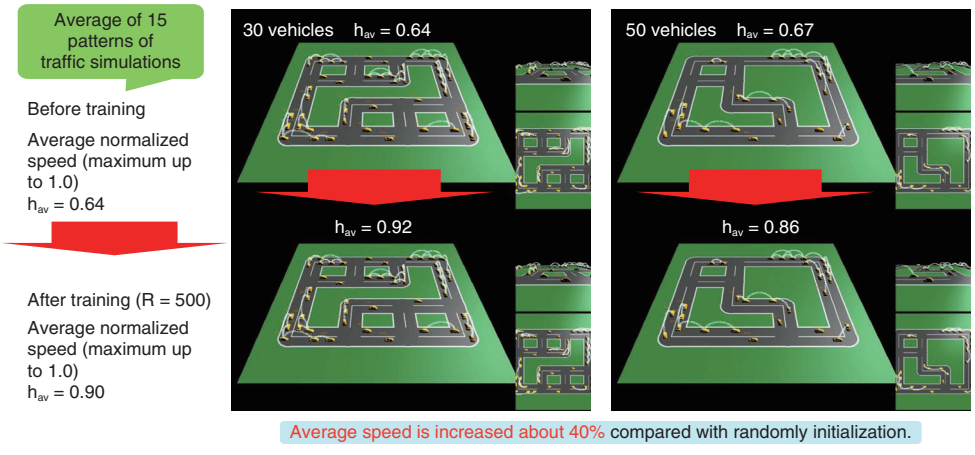


Fig. 4. Signal-free mobility system composed of prediction/control phase (left) and model-training phase (right).

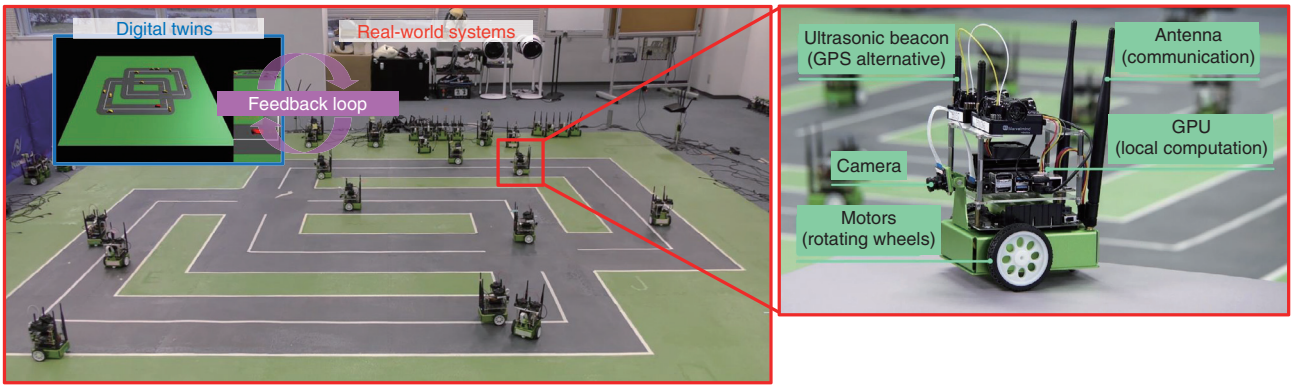


(a) Changes in average normalized speed through learning with each method



(b) Changes in average normalized speed through learning for a specified road setting with CoordiNet

Fig. 5. Experimental evaluation of model-training phase.



GPS: Global Positioning System

Fig. 6. Experiments on real-time traffic coordination using miniature autonomous vehicles.

states to be collision-free and a traffic simulator (Simulation of Urban MObility (SUMO)[*3]) for comparison. Using the GAT resulted in collisions from the start of the learning rounds, and the average speed could not be stably increased. When using SUMO, however, no collisions occurred, but vehicles would frequently stop in front of intersections, i.e., the average speed could not be increased.

To execute the prediction/control phase in real time using a trained traffic-coordination model (Fig. 4), a system to control miniature autonomous vehicles was constructed, as shown in **Fig. 6**. For each miniature autonomous vehicle, a pair of ultrasonic beacons for measuring position, graphics processing unit (GPU) for local computation, Wi-Fi communication module, and pair of motors to rotate wheels were implemented. In this system, each vehicle communicated with neighboring vehicles via a server and Wi-Fi, and vehicle states were predicted on the digital twins to shorten average travel time without collisions. Around 10–20 vehicles were controllable in real time (about 0.1–0.4-s intervals). Using this system, I experimentally confirmed that the vehicles could travel without collisions as the state predicted by the traffic-coordination digital twins.

3. Asynchronous decentralized federated learning project

In the signal-free mobility project, the system is implemented to learn a traffic-coordination model by aggregating data sets obtained via traffic simulators on a single server. However, its collective intelligence learning phase may be shifted to be a distributed manner.

The asynchronous decentralized federated learning project aims to train model parameters (e.g., in neural networks) under a massive network graph obeying a large number of nodes and edges. A pioneering study proposed FedAvg [2], which exchanges model parameters and averages them between connected nodes to make a consensus with each other. In contrast, the Edge-Consensus Learning (ECL) algorithm I proposed and its extensions [3, 4, 5] (i) make an arbitrary graph topology available, (ii) are robust to statistical data bias among nodes by imposing constraints on model consensus, and (iii) enable asynchronous decentralized communications, as shown in **Fig. 7**.

4. Future plans

I will investigate the mathematical foundation for learning collective intelligence and increase the number of application examples. My aim is to contribute to the early adoption of Digital Twin Computing into society through optimal control of huge systems.

*3 SUMO: An open-source traffic simulator used worldwide by researchers in the intelligent transport systems field. It can be downloaded at https://www.eclipse.org/sumo/.

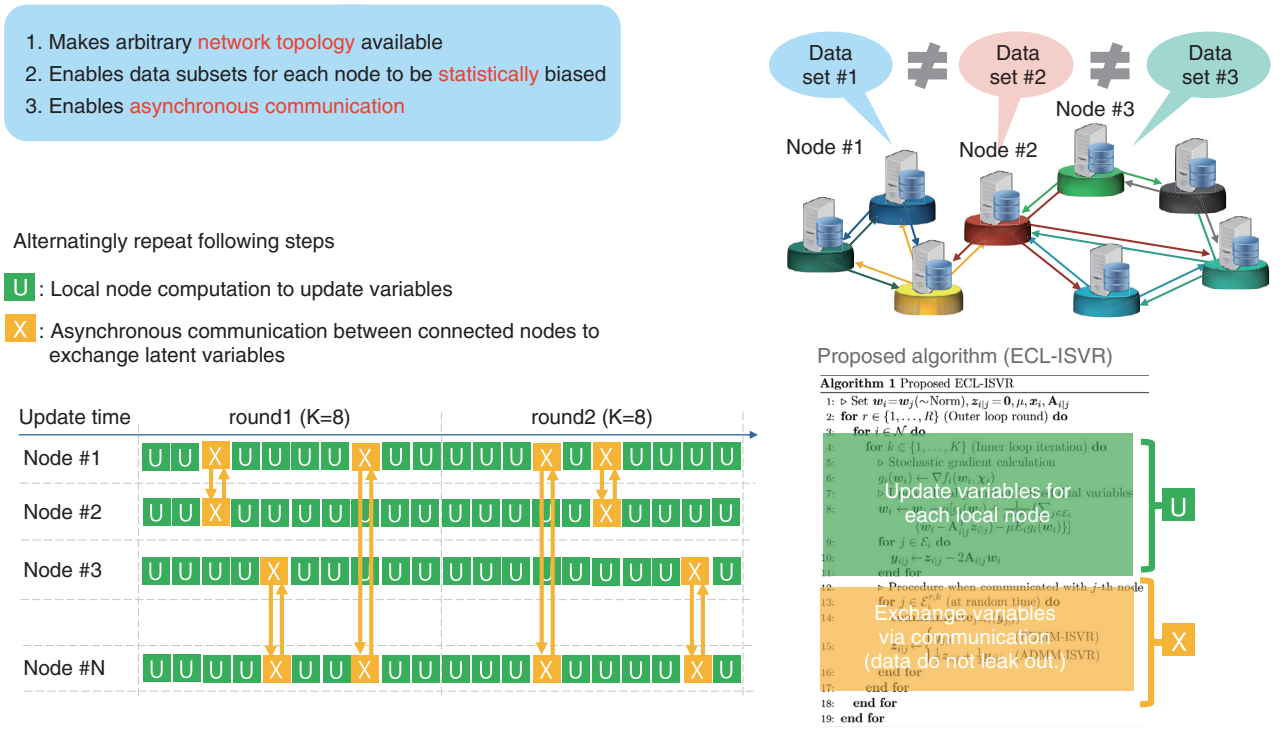


Fig. 7. Problem settings in asynchronous decentralized federated learning.

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Kenta Niwa

Distinguished Researcher, Learning and Intelligent Systems Research Group, Innovative Communication Laboratories, NTT Communication Science Laboratories.

He received his B.E., M.E., and Ph.D. in information science from Nagoya University in 2006, 2008, and 2014. Since joining NTT in 2008, he had been engaged in research on microphone array signal processing. From 2017 to 2018, he was a visiting researcher at Victoria University of Wellington and involved with research on distributed machine learning and mathematical optimization. He is now with NTT Communication Science Laboratories. He was awarded the Awaya Prize by the Acoustical Society of Japan in 2010. He is a member of IEEE (Institute of Electrical and Electronics Engineers).

Number Theory and Quantum Physics Based on Symmetry—Themes from Quantum Optics

Masato Wakayama

Abstract

The connection between mathematics and physics has produced many successes over the centuries. Modern mathematics is used, for example, in cosmology, high energy physics, and condensed matter theory. However, the connection between the theoretical study of quantum optics and modern mathematics, which is also necessary for the construction of quantum computers, is not always deep. In this article, I introduce the quantum Rabi model, which is the most fundamental theoretical model in quantum optics, and its relationship with modern mathematics, especially number theory, from the viewpoint of symmetry. I discuss the motivation for my research, how it has progressed, and future plans. I also introduce that mathematical conjectures arising from this study.

Keywords: non-commutative harmonic oscillator, quantum Rabi model, zeta functions

1. Mathematics and mathematical research

The purpose of mathematical research is to enrich mathematics by solving unsolved problems and discovering new problems, as well as by developing new mathematical visions and theories that can be applied to solutions of many problems. Mathematical research also gives rise to applications that are not immediately apparent. For instance, Riemannian geometry, developed in tandem with physicists, is largely independent from applications and is pure mathematics. It is now used, via Einstein's theory of general relativity, in making GPS (Global Positioning System) highly effective. Using the example of "research on quantum models and number theory from the viewpoint of symmetry" I describe my research motivation, objectives and results, and future goals based on them. The models mentioned in this article are the non-commutative harmonic oscillator (NCHO) [1], quantum Rabi model (QRM), and asymmetric QRM (AQRM) [2, 3].

Mathematics is, in part, an endeavor to understand, in a unified manner, facts that appear to be far apart, which sometimes takes quite long time. For example, there is the application of the discovery in ancient Greece of the infinity of prime numbers and uniqueness of prime factorization to today's public key cryptography. It took more than 2500 years to understand that mathematical discoveries can be used to maintain secrecy. Also, the structure of the universe is gradually being revealed through non-Euclidean geometry and group theory, which arose out of the human mind. We now know that economic phenomena and the movement of pollen can be understood in the same way since they are due to the mathematical description of Brownian motion, i.e., the development of stochastic analysis. In fact, there is a special value in the clarification of unquestionable affinities between subjects that have long been believed to be unrelated to each other. According to Henri Poincaré, mathematics is the art of identification. As Shin-Ichiro Tomonaga[*1] wrote: "What has worked well is experiment, demonstration/proof, and abstraction through mathematics. Abstraction makes it very

*1 Shin-Ichiro Tomonaga was a Japanese physicist, influential in the development of quantum electrodynamics, work for which he was jointly awarded the Nobel Prize in Physics in 1965 along with Richard Feynman and Julian Schwinger.

universal. These are the great strengths of physics." Mathematical theorems, however, are not invented but discovered. This becomes clear from Kunihiko Kodaira's view[*2] that mathematical research is, using paper and pencil, to dig out mathematical truths that do exist independent from human minds but are hidden.

The symmetry in the title refers to the actions of groups. We may recall the congruence transformation groups of Euclidean planes and spaces and the crystallographic groups familiar from physics and chemistry. Group theory was founded by Évariste Galois, who died in a duel at the age of 20. Before Galois, there were formulas for roots of quadratic, cubic, and quartic equations, and there were efforts to find those for quintic equations. However, what Galois did was to consider the entirety of the substitutions of the roots of an equation (the permutation group) and found from its structure that there is in general no root formula that uses the usual algebraic operations (addition, subtraction, multiplication, division) and application of radicals (square roots, cube roots, etc.) to coefficients of a polynomial when the equation is of fifth degree or higher[*3]. This is a major paradigm shift. What is the structure? It is related to the strength of the noncommutativity of the group. There is a large difference between putting on a suit after putting on a shirt and putting on a shirt after putting on a suit. I hope this gives an idea of non-commutative operations (actions).

2. NCHO

Quantum harmonic oscillators are fundamental in quantum theory. Their energies (eigenvalues) are given as half-integers in the standard normalization, and the corresponding eigenstates are Hermitian functions, i.e., given essentially by the Hermite polynomials times $e^{-\frac{x^2}{2}}$. A clean description of this can be obtained from the representation theory[*4] of the three-dimensional Lie algebra $\mathfrak{sl}_2(R)$ consisting of 2 × 2 matrices with trace 0. The $\mathfrak{sl}_2(R)$ captures the infinitesimal action of the Lie group $SL_2(R)$ formed by all real 2 × 2 matrices with determinant 1. Lie group theory originated from the work of Sophus Lie, who was impressed by the Galois theory of algebraic equations and wanted to construct a sort of Galois theory for algebraic differential equations. Lie groups are groups as the name implies and geometric objects called manifolds. In the geometric context, $\mathfrak{sl}_2(R)$ is considered as the tangent space of $SL_2(R)$ at the identity element of the group.

The Hermite functions form a basis of the Hilbert space $L^2(R)$ of square integrable functions on the real line. Many special functions, such as Hermite functions, Bessel functions, and Jacobi polynomials, are obtained by specializing one of the parameters a, b, or c of the Gaussian hypergeometric function $F(a, b, c; x)$ to integer values, etc. The differential equation (Gaussian ordinary differential equation (ODE)) satisfied by $F(a, b, c; x)$ has three regular singular points (e.g., 0, 1, ∞). The family of Gaussian hypergeometric functions is indispensable to the number theory of elliptic curves, which has been *the flower of mathematics* since the 19th century. In representation theory, however, special functions derived from Gaussian hypergeometric functions and its multivariable versions can be understood essentially as matrix elements of representations of Lie groups. I will now turn our attention to the following.

(1) The eigenvalues of (quantum) harmonic oscillators $H = a^\dagger a + \frac{1}{2}$, where a and $a^\dagger$ are

*2 Kunihiko Kodaira was the first Japanese recipient of the Fields Medal. The K3 surface, an important algebraic surface, was named by Andre Weil after three algebraic geometers (Kummer, Kaehler, Kodaira) and the then unexplored mountain K2. In the sixth night of Soseki Natsume's short story "Ten Nights of Dreams," there is a description of Unkei (a Japanese sculptor during the Kamakura period; 1150–1223) carving a statue of Nioh (the guardian gods of a temple gate) at the gate of Gokokuji Temple. One of the observers caught sight of Unkei and said, "He is not carving, he is just digging out the Nioh," which was originally buried in the wood. This is what Kodaira used to explain. Mathematics, which guarantees the reproducibility essential to science through rigorous proofs, is not a natural science that deals with physical nature, but rather a science that works toward the elucidation of mathematical nature.

*3 This is the beginning of Galois theory. Many mathematicians have become mathematicians because they were exposed to Galois theory. Although we now call it a "solution formula" for quadratic equations in Japan, it used to be called a "root formula," since a quadratic equation is one of various equations. However, I would like to use "root" with a special meaning because it is indeed a root which has broadened the world of mathematics.

*4 Representation theory is said to be the study of symmetry. It is at the intersection of algebra, geometry, and analysis, and is indispensable in mathematics that focuses on treating symmetry. In representation theory, each group element is represented by a linear transformation acting on a certain vector space (generally infinite dimensional) and the group product corresponds to composition of these transformations. We use the Weil representation (sometimes called the oscillator representation), the representation of $\mathfrak{sl}_2$ (R) given by the multiplication $\frac{1}{2}x^2$, the differential operator $-\frac{1}{2}\frac{d^2}{dx^2}$, and Euler's order operator $x\frac{d}{dx} + \frac{1}{2}$. (For an introduction to the Weil representation, see R. Howe and E-C. Tan, "Non-Abelian Harmonic Analysis: Applications of $SL(2, R)$," Springer, 1992.)

respectively the creation and annihilation operators subjecting $[a^\dagger, a] = 1$, are half-integers. Therefore, the spectral zeta function[*5] of the harmonic oscillator determined from the eigenvalues essentially coincides with the Riemann zeta function $\zeta(s)$[*6].

(2) The symmetry of $SL_2(R)$ remains in the world of Gaussian hypergeometric functions. For instance, the matrix elements of representations of $SL_2(R)$ and, almost equivalently, the solution of the $SL_2(R)$-invariant differential equation all can be expressed essentially by Gaussian hypergeometric functions.

The group $SL_2(R)$ is behind (1) and (2) above. To explore the wider world, we need to weaken the symmetry. The only noncommutative property of harmonic oscillators is the canonical commutation relation (CCR) controlled by $\mathfrak{sl}_2(R)$[*7]. The NCHO[*8], which defines a system of ODEs, with two parameters α and β, adds matrix noncommutativity. The name comes from this noncommutativity. Of course, it would not be rational to define it in an arbitrary manner. From expected physical applications and corresponding mathematically reasonable consideration, we thought that it should be at least required that the Hamiltonian Q of the NCHO have only real discrete eigenvalues and that it be kept a sufficiently weak symmetry to allow the harmonic oscillator to be recovered when $\alpha = \beta$. The former requires that Q be a positive Hermitian operator (i.e., self-adjoint operator). The latter is that the spectral zeta function $\zeta_Q(s)$ of Q be a good generalization of $\zeta(s)$ though neither a functional equation nor Euler product may be expected [4].

The convergence region of the defining series of $\zeta(s)$ is only in the half-plane, while $\zeta(s)$ has analytic continuation to the whole plane. The Riemann Hypothesis[*9] asserts that the real part of an imaginary number s with $\zeta(s) = 0$ is always $\frac{1}{2}$. There are two analogues of the Riemann Hypothesis at the top (and among the best-known achievements) of 20th century mathematics. One is the Weil Conjecture for the congruent zeta function and the other is the Selberg zeta function for the prime geodesic distribution. Both conjectures were settled by the fact that each zeta function has a determinant expression in terms of suitable Hermitian operators[*10]. The study of a possible determinantal expression of $\zeta(s)$ is also important in the attack on the original Riemann Hypothesis.

3. QRM and NCHO

Isidor Isaac Rabi described the interaction of classical light with atomic quantum states in 1936. In 1963, Edwin Jaynes and Fred Cummings quantized light as well and defined the QRM and its rotating wave approximation, now known as the Jaynes-Cummings model. However, while the integrability of the QRM was unknown, the Jaynes-Cummings model was useful because of the existence of continuous invariants, making the theoretical treatment easy, and suitability to experiments if the light-matter coupling is very weak, roughly a fraction 10^{-6} of the mode frequency[*11].

However, with the possibility of developing a quantum computer on circuit quantum electrodynamics (QED) platforms, the weak coupling approximation is no longer justified, and one must use the QRM in the ultra-strong coupling regime. In 2011, Daniel Braak [2] demonstrated the integrability of the QRM, and research on the periphery of the QRM has advanced rapidly since. In fact, the experimental measurement results [5] using superconducting

*5 The spectral zeta function of an operator with positive eigenvalues $\lambda_1 \leqq \lambda_2 \leqq \lambda_3 \leqq \ldots$, where the multiplicity of the eigenvalue is uniformly bounded, is defined by the Dirichlet series $\lambda_1^{-s} + \lambda_2^{-s} + \lambda_3^{-s} + \ldots$.

*6 $\zeta(s) := 1 + 2^{-s} + 3^{-s} + 4^{-s} + 5^{-s} + \cdots = (1-2^{-s})^{-1} \times (1-3^{-s})^{-1} \times (1-5^{-s})^{-1} \times (1-7^{-s})^{-1} \times (1-11^{-s})^{-1} \times \cdots$ (Euler's product) for a complex number s, the real part of which is greater than 1. The spectral zeta function is in fact identified with $(2^s - 1)\zeta(s)$.

*7 Define $h = a^\dagger a + \frac{1}{2}$, $e^+ = \frac{1}{2}a^{\dagger 2}$ and $e^- = -\frac{1}{2}a^2$, then the triplet $\{h, e^+, e^-\}$ forms the Lie algebra $\mathfrak{sl}_2(R)$, that is, the commutation relations $[h, e^\pm] = \pm 2e^\pm$ and $[e^+, e^-] = h$ hold. Here $h = 2H + \frac{1}{2}$ for the Hamiltonian of harmonic oscillator $H = \frac{1}{2}a^\dagger a$.

*8 The Hamiltonian Q of the NCHO is of the form $Q := \begin{pmatrix} \alpha & 0 \\ 0 & \beta \end{pmatrix} \left(-\frac{1}{2}\frac{d^2}{dx^2} + \frac{1}{2}x^2\right) + \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \left(x\frac{d}{dx} + \frac{1}{2}\right)$, where α and β are positive and $\alpha\beta > 1$. The condition on α and β guarantees that Q has only positive and discrete eigenvalues with uniformly bounded multiplicity.

*9 It is still unsolved more than 160 years after being stated by Riemann (1859). This conjecture, which has been challenged by many geniuses, is equivalent to the ultimate distribution of primes, as shown in 1901 by Helge von Koch. Koch is famous for the Koch snowflake/curve, after whom it is named.

*10 The congruence determined for smooth algebraic manifolds and schemes over finite fields was positively solved in the case of zeta functions by the determinantal expression of what is called the Frobenius operator, and in the case of Selberg zeta functions by the Laplacian, the (unique up to a constant) invariant differential operator on the complex upper half-plane.

*11 The Nobel Prize in Physics 2012 awarded to Serge Haroche and David J. Wineland for their groundbreaking experimental method for the measurement and manipulation of quantum systems seems to be at the center of this trend.

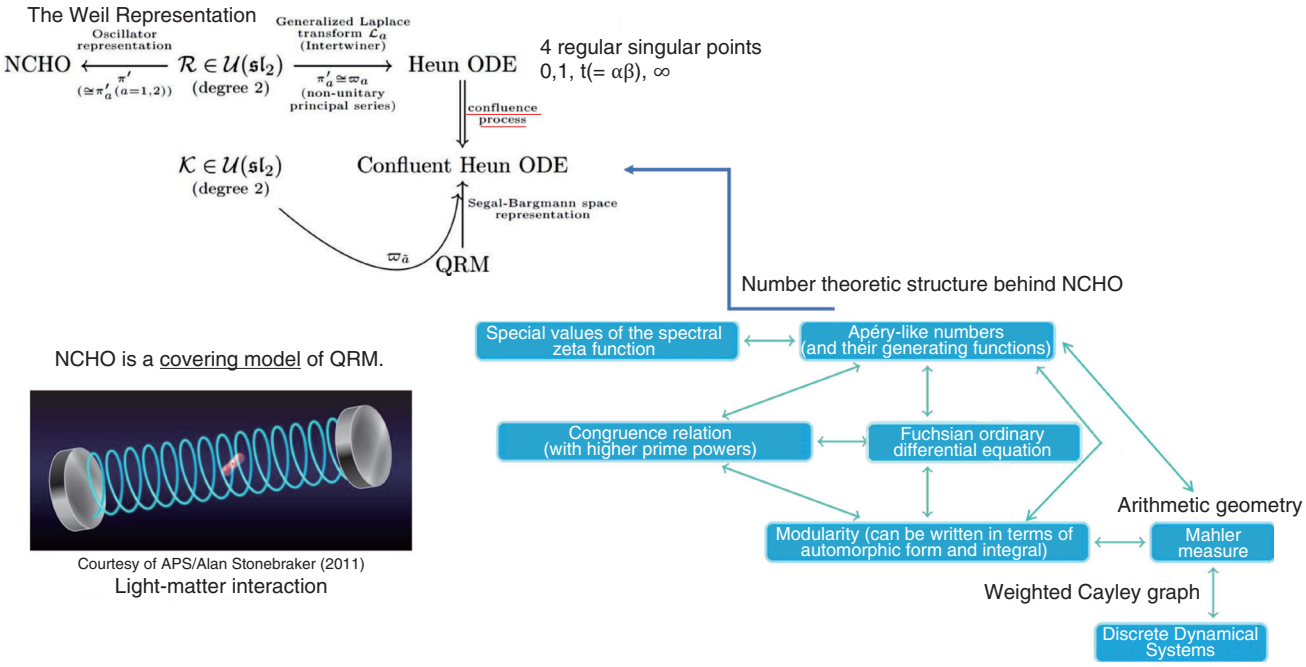

Fig. 1. NCHO & QRM.

artificial atoms were consistent with the theory of the QRM and its generalization, the AQRM (see also [6]).

The NCHO has expanded the world from Gauss's as expected. In fact, the eigenvalue problem of the NCHO was found to be equivalent to the existence of holomorphic solution of the Heun ODE[*12] in the complex region containing 0, 1, and not including $\alpha\beta$. This fact was discovered by Hiroyuki Ochiai [7] and fully understood 15 years later [8]. The (A)QRM also has a Heun picture [2]. However, unlike the NCHO, it is a confluent Heun differential equation. Nevertheless, by merging the two singularities as $\alpha\beta \to \infty$, a confluent Heun picture of the QRM can be obtained from the Heun picture of the NCHO [8]. In other words, the NCHO can be considered as a covering model of the QRM[*13] (**Fig. 1**, the NCHO is a covering model of the QRM).

Quantization is discretization and passing from a commutative world to a non-commutative world. The former is the original arena of number theory. In fact, the special values of $\zeta_Q(s)$ in the NCHO shows rich number theory as I explain below. For instance, as to the special values of the spectral zeta function of the harmonic oscillator, essentially given by $\zeta(s)$, there is the old Basel problem to determine the value of the infinite series $1+\frac{1}{4}+\frac{1}{9}+\frac{1}{16}+\frac{1}{25}+\cdots$[*14], which was solved by Euler. The even integer values of $\zeta(s)$ are generally expressed in terms of powers of π and rational numbers. However, the value and properties of $\zeta(s)$ at odd points remained unknown for more than 300 years until Roger Apéry's proof that $\zeta(3)$ is irrational in 1978. The best result on irrationality is still the theorem that at least one of $\zeta(5)$, $\zeta(7)$, $\zeta(9)$, or $\zeta(11)$ is an irrational number. However, the research on special values is a deep problem in modern mathematics, such as the geometric conjecture on special values of various zeta functions by Pierre Deligne[*15] who solved the Weil Conjecture using Grothendieck's arithmetic geometry, and the Birch-Swinnerton-Dyer

*12 The Heun equation is a second-order ODE of Fuchsian type with four fixed singular points, e.g., (0, 1, t, ∞). Unlike Gaussian hypergeometric functions, there are aspects of its mathematical structure that need to be clarified, but they appear in the description of various physical phenomena. The Gaussian hypergeometric equation can be considered a degenerate case of the Heun equation. This is the first meaning for expanding the world from Gauss's.

*13 This is also true for the AQRM by adding an appropriate shifted (biased) term to the NCHO.

*14 In terms of the special value of $\zeta(s)$, $1+\frac{1}{4}+\frac{1}{9}+\frac{1}{16}+\frac{1}{25}+\cdots = \zeta(2) = \frac{\pi^2}{6}$. The appearance of π was a great surprise.

*15 Fields Medal 1978.

conjecture on special values at the central point of *L*-functions (relatives of zeta) defined from elliptic curves and its generalization by Bloch, Beilinson, and Kato.

Apéry used a sequence of rational numbers, now called the Apéry numbers, to prove the impossibility that $\zeta(3)$ is rational. Frits Beukers took up the challenge of finding out why and further proving irrationality and developed a brilliant study of elliptic curves, *K*3 surfaces, and automorphic forms behind the proof of the irrationality [9]. As a result, he showed remarkable congruence relations of the Apéry numbers, which have become the subject of research in algebraic number theory. Surprisingly, the special values $\zeta_Q(2)$ and $\zeta_Q(3)$ for the NCHO also yield sequences of numbers with properties like those of the Apéry numbers [10, 11, 12]. Elliptic curves and automorphic forms underlie these properties, and when $s = 4$, even automorphic integrals[*16], which generalize the notion of automorphic forms, appear [10] via certain nearly holomorphic automorphic forms initially studied by Goro Shimura[*17]. The next development will be the study of a wider range/class of automorphic forms (also related to the Langlands program, which is extremely important in mathematics [13]).

4. Spectra of the AQRM and hidden symmetries

The importance of the partition function (weighted sum of states) in statistical mechanics is that it encodes the time evolution of the system. Knowing the exact behavior of a quantum system during a long period is of utmost importance to any task in quantum computing. Purely numerical approaches are severely limited due to the accumulation of rounding errors in the long-time limit. Therefore, it is necessary to derive analytical formulas for its heat kernel and partition function. In fact, the partition function and spectral zeta function have a one-to-one correspondence through the Mellin integral transform. However, obtaining these analytical formulas was considered extremely difficult. Physicists use a highly intuitive form of expression called Feynman path integral to carry out various asymptotic or approximate (as well as precise) calculations to gain a better understanding of the physical system of interest. The translation invariant measure and integral on the space of paths cannot be treated mathematically in a rigorous manner, except in some special cases. Of course, various studies are still ongoing to understand it. I, together with Reyes-Bustos, have attempted to derive a heat kernel for the (A)QRM[*18]. The method, which has been successfully applied [14], is based on the action of the symmetric group $\mathfrak{S}_m$ of the *m*th order on $Z_2^m (m = 1,2,...)$, the Fourier transform on Z_2^m[*19], and graph theory, where Z_2 is $Z/2Z$ or the field of two elements $F_2 = \{0,1\}$. The resulting analytic formula is practically given by the series over non-negative integers *m* for integrals over *m*-simplex (an *m*-fold integral) of elementary functions given by products and quotients of exponential functions. It can also be interpreted as the infinite sum (integral) of the orbit integrals of $\mathfrak{S}_\infty$ over the entire equivalence class by the infinite symmetric group $\mathfrak{S}_\infty$ of discrete paths connecting 0 and ∞ (**Fig. 2**, Discrete paths and infinite symmetry groups (Geometric Interpretation)). From a representation theoretic point of view, the action of $\mathfrak{S}_\infty$ on Z_2^∞ corresponds to a decomposition into the direct sum of irreducible representations (**Fig. 3** (Algebraic Interpretation)). The formulas obtained are similar to formulas for partition functions obtained for the spin-boson model or the Kondo model (describing magnetic impurities in non-magnetic host metals, named after Jun Kondo, 1930–2022), a formally exact description of the matrix element of the heat kernel, and to approximate partition functions for various physical systems. For a general model, the (possible) existence of an infinite-dimensional algebraic system acting on the non-countable paths of the Feynman integrals and the acquisition of discrete paths as their equivalence analogue should also be pursued (**Fig. 4**, Conjecture on the paths of the Feynman path integral).

From the analytical formula for the heat kernel, the partition function is obtained, and the contour integral expression of the spectral zeta function is gained[*20]. Thus, the analytic connection to the whole plane is obtained, the asymptotic evaluation of the number of eigenvalues (Weyl's law) follows, and we can start the special value study [15]. What is the number theory and geometric structure of the QRMs?

*16 Also called the Eichler form.

*17 This fact means that the second reason we can expand the world from Gauss's. The notion of automorphic integrals (sometimes called Eichler's forms) appeared in [10] is a further reasonable extension of the standard one.

*18 The Trotter-Kato product formula is the starting point for the heat kernel derivation; it is useful to derive the Feynman path integral formally, or even considered as the rigorous description of the Feynman path integral.

*19 It is a part of the action of the oscillator representation of $SL_2(F_2)^n$. This representation is used for the construction of quantum error correcting codes such as Clifford cord.

*20 The contour integral is a path starting from the infinity point ∞, circling around the origin 0, and returning to ∞.

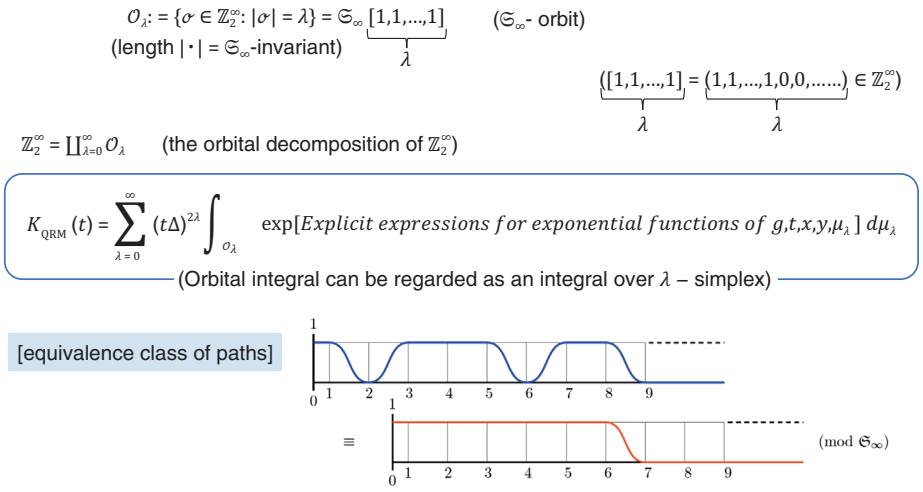

Fig. 2. Heat Kernel Formula – Geometrical Interpretation.

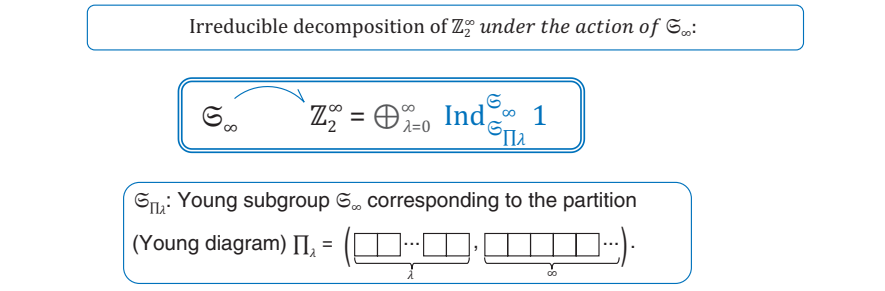

Fig. 3. Heat Kernel Formula – Algebraic (Group Theoretic) Interpretation.

This is one of the most important questions in this area.

The AQRM is of major importance in circuit QED implementations of the QRM, thus for applications to quantum computing. Unlike the QRM, it has no visible Z_2-symmetry (parity), if the bias is not zero. Nevertheless, it shows characteristic spectral degeneracies at half-integer values of the bias parameter. In fact, the AQRM is degenerate if and only if the bias parameter (of the bias operator) of the Hamiltonian*21 is a half-integer $\ell/2$ ($\ell \in Z$) [3, 16]. In physics, however, degeneracy is considered to indicate the existence of a symmetry [17]. Unlike classical mechanics, the concept of integrability is not clear in quantum mechanics [18]. However, the analogy with classical systems has led to the search for operators that commute with H_{AQRM} but are not functions of H_{AQRM}, indicating the presence of an additional conserved quantity [19]. Inspired by this study, we [20] conducted a thorough analysis to completely determine the operators that are commuting with the H_{AQRM}. Interestingly, the ring*22 of operators commuting with H_{AQRM}, has a unique natural generator J_ℓ

*21 The AQRM Hamiltonian has the form $H_{AQRM} = a^\dagger a$ [photon field] + $\frac{\Delta}{2}\sigma_z$ [two-level atom] + $g(a + a^\dagger)\,\sigma_x$ [interaction term] + $\epsilon\sigma_x$ [bias term (given by a real number)], where σ_* is Pauli matrix, Δ is the energy difference of the two level atom and g the coupling (interaction) constant. We notice that the bias term given by $\epsilon \in R$ of H_{QRM} is zero. Note that after its proposal in [2], the AQRM (as it is now called) was called the "generalized" QRM, "biased" QRM, "driven" QRM, etc., but after [3], "asymmetric" QRM became established.

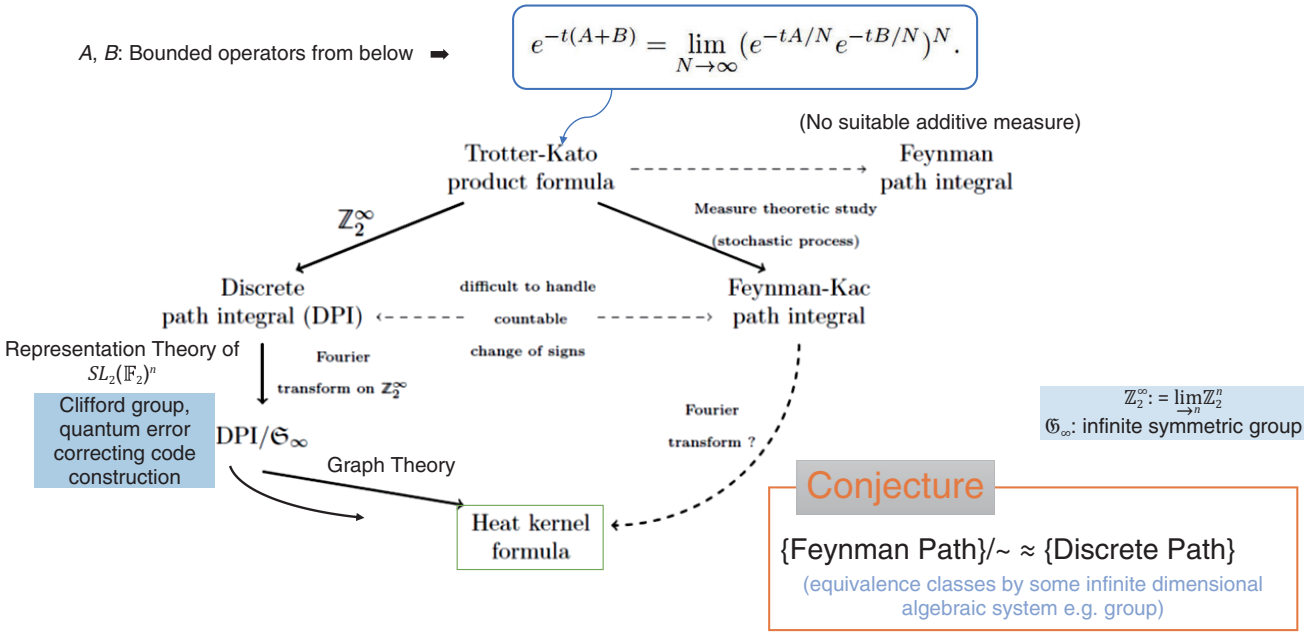

Fig. 4. Product Formulas of Trotter-Kato ➡Heat Kernel, Propagator.

up to a constant multiple. Moreover, the square of J_ℓ is expressed as ${J_\ell}^2 = p_\ell(\mathrm{H_{AQRM}}, g, \Delta)$, a polynomial in $\mathrm{H_{AQRM}}$, where p_ℓ is an ℓth degree polynomial. The equation $y^2 = p_\ell(x; g, \Delta)$ defines a hyperelliptic curve [21].

On the other hand, the degenerate eigenvalues of the AQRM are of the form $N \pm \frac{\ell}{2} + g^2$ with positive integer N. Fixing N and ℓ, (g^2, Δ^2) is obtained as zeros of the constraint polynomial $P_{N+\ell}^{(-\ell/2)}(g^2, \Delta^2)$ and $P_N^{(\ell/2)}(g^2, \Delta^2)$ [12]. In fact, $P_N^{(\ell/2)}(g^2, \Delta^2)$ divides $P_{N+\ell}^{(-\ell/2)}(g^2, \Delta^2)$, and the quotient polynomial is $A_\ell^N(g^2, \Delta^2)$ (>0) [16]. It should also be noted that the AQRM degeneracies are, geometrically, conical intersection points in the three-dimensional spectral graph (Left of **Fig. 5**).

From experimental calculations, we know that $A_\ell^N(g^2, \Delta^2) = p_\ell\left(N - \frac{1}{2} + g^2, g, \Delta\right)$ $(\ell \le 6)$. If this holds in general, the expectation "hidden symmetry behind the degeneracy" becomes explainable concretely provided we may think of the existence of a non-trivial operator commuting with the Hamiltonian (which is in fact an involution modulo the Hamiltonian) as evidence of quantum integrability*23 (Fig. 5 and **Fig. 6**). There is, however, no way to prove it, and it remains a conjecture [21]. However, this conjecture is very similar in form to a certain theorem*24 in the Diophantine geometry*25 [22] in its form. Therefore, a clue to the proof might be found there. We also expect that the AQRM has a finite number of degenerate eigenvalues for fixed parameters g and Δ. Although it is still unresolved, we can find some formal similarities with the Mordell Conjecture*26 in this case.

*22 It is an algebraic system closed in addition and multiplication except for division, such as the whole of integers (integer ring) and the whole of polynomials (polynomial ring).

*23 We can define a new mathematical model that we call the shifted NCHO. This model gives the covering model of the AQRM by looking at each Heun ODE picture for the shifted NCHO and AQRM, respectively. Since the model keeps the apparent parity symmetry at the Hamiltonian level, the hidden symmetry of the AQRM may also be explained as the inheritance of this parity symmetry.

*24 This theorem is closely related to the well-known Vojta Conjecture. The Vojta Conjecture is also a higher dimensional version of the Mordell Conjecture and closely related to the ABC Conjecture.

*25 A fundamental theme in number theory concerns the study of integer and rational solutions to Diophantine equations (polynomial equations). This topic originated at least 3,700 years ago as documented in Babylonian clay tablets. There are interesting interactions between Diophantine Geometry and several fields such as representation theory, algebraic geometry, topology, complex analysis, and mathematical logic, to mention a few, which have been found to be quite fruitful.

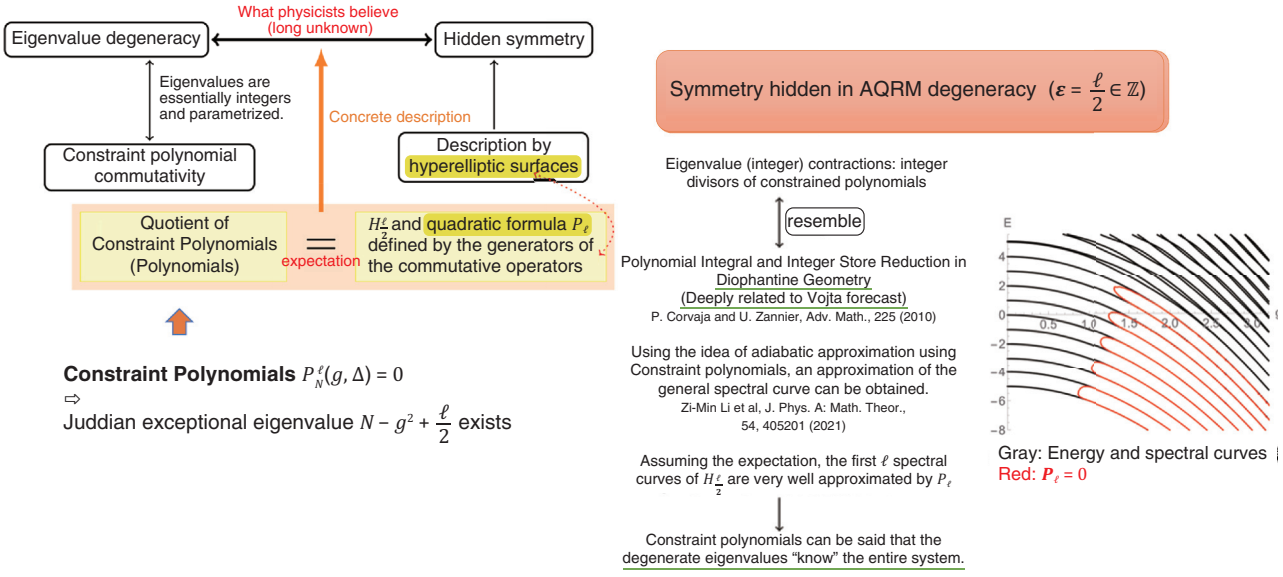

Fig. 5. Clarification of the underlying fundamental reason is expected.

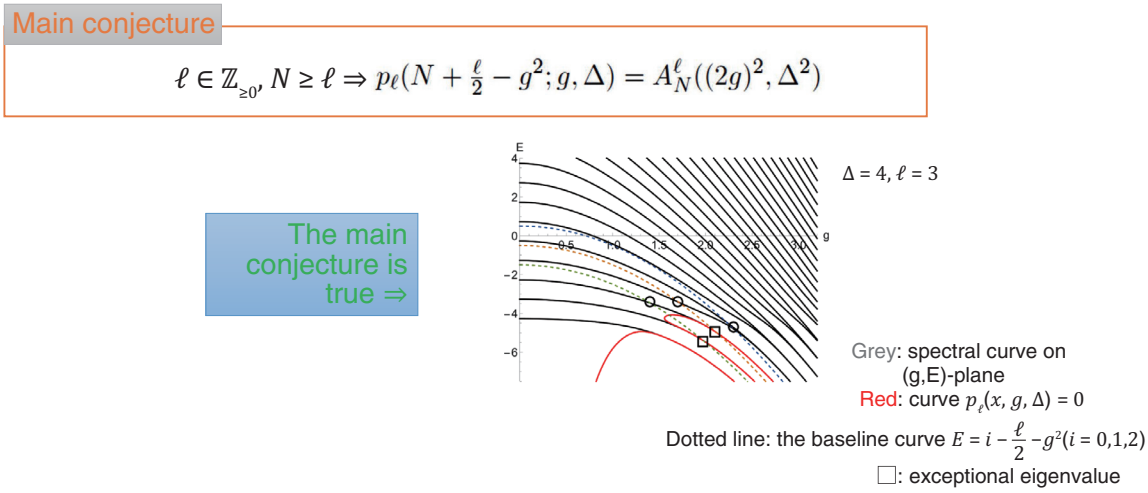

Fig. 6. The degenerate eigenvalues may "know" the entire spectrum of the system.

5. Conclusion

Let us discuss a few phrases that characterize mathematics. First, "All things are numbers" by Pythagoras. This is reminiscent of the big data and artificial intelligence (AI) that dominate modern society. The genius Leonardo da Vinci said, "Engineering is the paradise of the mathematical sciences. After all, it is here that the fruits of mathematics are borne." Galileo Galilei's "The universe is written in mathematical language" is well known. Wigner's "The unreasonable effectiveness of mathematics in the natural sciences,"*27 is a brilliant point.

Although mathematical research is like musical composition in some respects, it has been difficult to find a mechanism to make mathematical papers play

*26 The conjecture that a curve with a number of holes (genus) greater than 1 defined on a rational number field would have only a finite number of rational points, proved by Gerd Faltings in 1983.

like music, such as reproducing a symphony from a score. However, the use of mathematics has emerged because of machine learning, AI, and other technologies. Although the motivations for research are diverse, including pure mathematics driven solely by curiosity, it now seems as if an opportunity has arrived for basic mathematics and applied mathematics to play a brilliant concerto. I close this article with the hope that a new "mathematical music" (in Japanese, we may express it as 数楽 (su-gaku) meaning enjoining mathematics and is a homonym with 数学 (su-gaku) meaning the study of numbers, i.e., mathematics)[*28].

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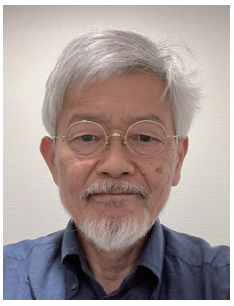
*27 The following is an excerpt from a lecture transcript published in 1960 by Eugene Wigner (1902–1995: Nobel Prize in Physics 1963, "Discovery of Symmetry in the Theory of Nuclei and Elementary Particles"). Wigner's remark echoes a well-known sentence by Einstein, who said, "Das ewig Unbegreifliche an der Welt ist ihre Begreiflichkeit." in English: "The fact that the universe is comprehensible [by mathematical means] is utterly incomprehensible."

*28 Many professions in academia, e.g., scientist, physicist, chemist, and linguist end in "st." However, astronomer and geometer end in "er." Magician, musician, and mathematician end in "cian," and their initial letter is "m." Perhaps there might be some influence of liberal arts education (the seven liberal arts) dating back to ancient Greece and Rome, but it is not easy to explain immediately. It is just interesting to notice.



Masato Wakayama
Head and Fundamental Mathematics Research Principal of NTT Institute for Fundamental Mathematics.

He graduated from Tokyo University of Science in 1978 and completed a doctoral course at Hiroshima University's Graduate School of Science in 1985 (Doctor of Science). Before becoming a research principal at NTT Institute for Fundamental Mathematics on October 1, 2021, he had held many other academic positions: an associate professor at Tottori University and Kyushu University, visiting fellow at the Department of Mathematics, Princeton University, visiting professor at the University of Bologna, distinguished lecturer at Indiana University (Bloomington), distinguished professor in Mathematics, Dean of the Graduate School of Mathematics, Kyushu University, the first director of the Institute of Mathematics for Industry, executive vice president of Kyushu University, and vice president and professor of Tokyo University of Science. He is also a principal fellow of CRDS (Center for Research and Development Strategy, Japan Science and Technology Agency), and a professor emeritus of Kyushu University. He specializes in representation theory, number theory, and mathematical physics.

Development of a Rust Removal Tool Using a Diffractive Optical Element and High-power Laser and Its Application to Asbestos-melting Tools

Sohan Kawamura and Kaori Takayanagi

Abstract

To improve the efficiency of rust removal on telecommunication towers, we developed a prototype of a compact, lightweight rust-removal tool using a diffractive optical element and high-power laser that weighs only 500 g. With the aim of applying this technology to asbestos removal, we experimentally irradiated asbestos with a laser, and the results of the experiment suggest that using a laser in this manner can melt and remove asbestos and reduce its risk as a health hazard to workers.

Keywords: infrastructure, high-power laser, diffractive optical element

1. Introduction

NTT possesses a large amount and wide variety of infrastructure facilities that are indispensable for implementing NTT's concept called the Innovative Optical Wireless Network (IOWN). To efficiently maintain these facilities, NTT is researching and developing technology that involves using high-power lasers and diffractive optical elements. In this article, a rust-removal tool using a high-power laser and diffractive optical element is described, and the results of experiments conducted to apply this technology to asbestos removal are presented.

2. Development of rust-removal tool

NTT maintains 20,000 telecommunication towers, many of which are several decades old, so it is essential to remove rust from and repaint them to prevent them from deteriorating. Currently, electric tools are used to remove rust; however, the space around bolts is too tight for electric tools to remove the rust there. Lasers have been attracting attention as a means of removing rust. Lasers can melt and vaporize rust without contacting it, so rust can be removed from confined spaces without damaging the base material. However, a conventional laser system consists of a mechanical-drive unit that scans a laser beam (focused by a lens) in two dimensions, and the system is large and heavy, weighing about 2 kg, thus difficult to use high above the ground in places such as the upper reaches of telecommunication towers.

Given the above-described circumstances, NTT aimed to develop a small, lightweight rust-removal tool that can be used high above the ground. We have developed a prototype rust-removal tool—weighing only 500 g—that can be held in one hand. We achieved this by eliminating the conventional mechanical-drive unit, which was replaced with a diffractive optical element for forming the laser beam with a narrow, linear intensity distribution and moving the shaped laser beam by hand [1]. The prototype laser system and examples of using it for removing rust are shown in **Fig. 1**. To prevent rust forming on steel towers, it is also important to prevent the paint from peeling off after the rust is removed. Accordingly, we confirmed that this technology (i.e., rust-removal tool) leaves sufficient paint adhesion to

Fig. 1. Prototype rust-removal tool (left) and example of rust removal (right) [1].

prevent rusting.

3. Application to asbestos removal

3.1 Demand for asbestos removal

Some of the facilities owned by NTT include buildings that contain asbestos, which must be removed when the building is demolished or renovated. However, there are several issues with methods of removing asbestos. We are therefore also researching the above technology to apply it to removing asbestos from buildings.

Asbestos is a fibrous substance that has been produced and used in large quantities since the 1920s because of its excellent heat and chemical resistance. In the 1950s, however, asbestos was found to cause lung cancer, and its production and use were banned in Europe from the 1990s and in Japan in 2004 [2–5].

According to Japan's Ministry of Land, Infrastructure, Transport and Tourism, the number of demolitions of buildings containing asbestos in Japan has increased and is estimated to reach 100,000 buildings around 2028. The demand for demolition work is estimated to continue for about 30 years [6]. Those buildings are being demolished after asbestos-containing painted materials are removed by using power tools or water jets.

However, power tools invariably scatter asbestos, so equipment is needed to prevent leakage of asbestos and exposure of workers to it. If water jets are used, scattering of asbestos can be controlled, but it is difficult to remove asbestos from narrow spaces, and equipment for filtering water mixed with asbestos is essential.

Asbestos-containing materials that have been removed are either melted down to eliminate its fiber structure and reused or disposed of as landfill. Owing to the above-mentioned increase in demolition work in the future, it is a concern that there will be the shortage of asbestos-treatment facilities and landfill sites. Asbestos-treatment technology that enables low-cost and efficient reuse is thus required [7].

We are researching and developing technology for reducing the risk of worker exposure to asbestos and leakage of asbestos by using high-power lasers to remove asbestos in a manner that melts it and destroys its harmful fibrous structure. High-power lasers can melt asbestos in a non-contact manner, so it becomes possible to remove asbestos in narrow spaces from which it cannot easily be removed with power tools or water jets. Hereafter, an experiment in which asbestos was melted by using a laser is described.

4. Asbestos-melting experiment

4.1 Sample preparation

Chrysotile ($Mg_3SiO_5(OH)_4$) powder, i.e., the most common form of asbestos, was used to confirm that laser melts asbestos. To observe the dust generated by laser irradiation of asbestos-based coating materials, coating materials collected from buildings were used in the experiment. The coating material consists of a base coat, main coating material, and top coat. Asbestos is used as the base-coat material when mixed with mortar. The appearance and cross section of an asbestos-containing coating material taken from a building and used in this experiment are shown in **Fig. 2**. The thickness of the base coat of the sample

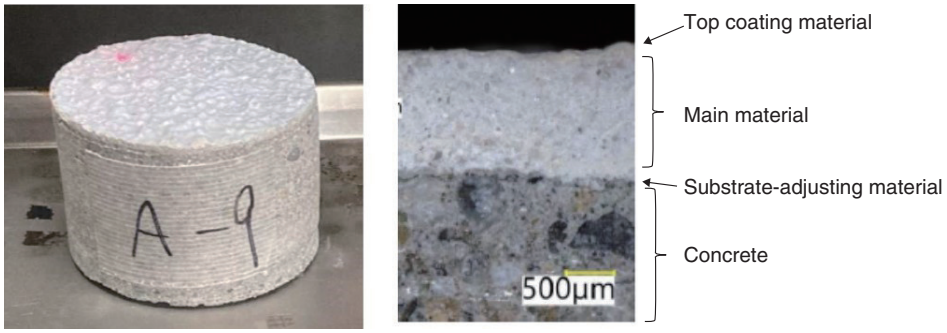


Fig. 2. Appearance (left) and cross-sectional view (right) of asbestos-containing coating material collected from a building [8].

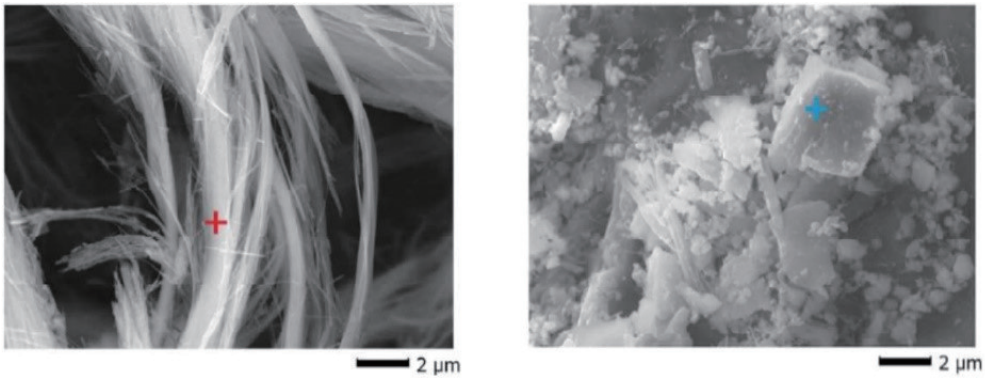


Fig. 3. Electron micrographs of chrysotile (left) and laser-irradiated chrysotile (right) [8].

was about 50 μm, and the concentration of the asbestos (chrysotile) contained in the sample was 1 wt%.

4.2 Laser-irradiation experiment

A pulsed laser—with average output of 100 W, frequency of 100 kHz, and wavelength of 1.06 μm—was used. The laser beam emitted from the light source was focused using an fθ lens to spot diameters of 50 and 140 μm and scanned in two dimensions with a galvanometer mirror over an area of 8 × 8 mm.

To qualitatively estimate the amount of asbestos dispersed by laser irradiation, the dust generated by laser irradiation was captured with a high-speed camera. It was assumed that the amount of asbestos dispersed was proportional to the amount of dust generated. The sample was illuminated using a laser with a wavelength of 532 nm and, simultaneously, a high-power laser with a wavelength of 1.06 μm. The light with the wavelength of 532 nm reflected by the dust was captured with the high-speed camera, and the amount of dust was qualitatively evaluated from the intensity of the reflected light.

4.3 Experimental results

Electron micrographs of the chrysotile before and after laser irradiation are shown in **Fig. 3**. It is clear that the laser irradiation destroyed the fibrous structure of the chrysotile. Analysis of the composition of the particles observed after laser irradiation showed that particles containing magnesium and silicon were generated. Therefore, it is considered that the particles were the result of the chrysotile melting then solidifying.

The results of qualitatively estimating the amount of dust on the coating material (collected from a building) when it was irradiated with the pulsed laser are plotted in **Fig. 4**. Images of the dust were captured with a high-speed camera, the brightness in the images was calculated, and the amount of dust was estimated from the calculated brightness.

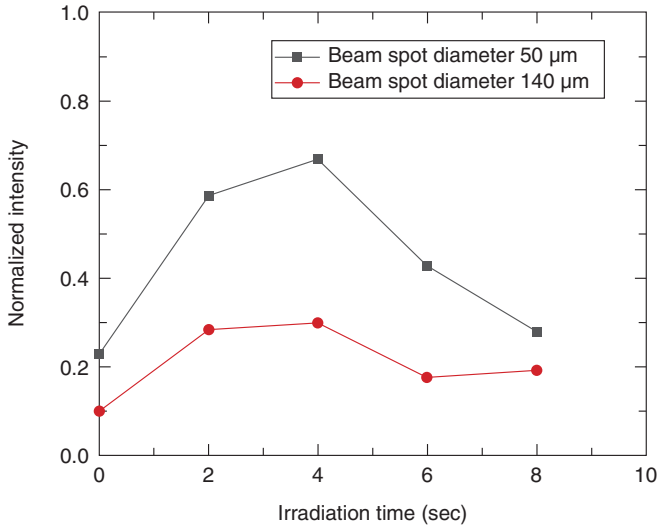


Fig. 4. Example of brightness measurement using a high-speed camera image when beam diameter is changed [8].

Since the brightness of the image changes by changing the beam diameter, it can be assumed that the amount of dust also changes. This suggests that the dust can be suppressed by appropriately controlling the laser-irradiation conditions. An example of one of the particles in the dust, as observed with an electron microscope, is shown in **Fig. 5**. Analysis of the composition of such particles showed that they contained magnesium and silicon, suggesting that the particles were the result of the chrysotile in the coating material melting and solidifying. It also suggests that irradiating asbestos with a laser can prevent it from being dispersed while it is still harmful. We believe that the use of a diffractive optical element in the manner described above can improve the efficiency of asbestos-removal operations.

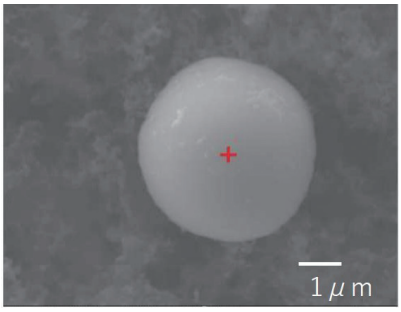


Fig. 5. Electron micrograph of a particle in dust generated by laser irradiation.

5. Summary

A compact, lightweight rust-removal tool—weighing only 500 g—using a high-power laser and diffractive optical element was developed for efficiently removing rust from communication towers. We are researching the application of this tool to the removal of asbestos, which involves melting the asbestos during the demolition and renovation of asbestos-containing buildings. We conducted an experiment in which asbestos was irradiated with a high-power laser beam. The results of this experiment suggest that asbestos can be melted and asbestos dust can be suppressed by appropriately controlling the laser-irradiation conditions.

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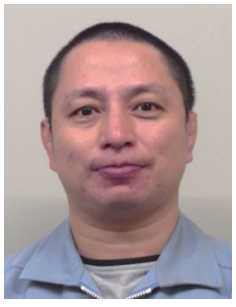


Sohan Kawamura
Research Engineer, Smart Maintenance and Management Technology Development Project, Health and Environmental-Sensing Device Project, NTT Device Innovation Center.
He received a B.E., M.E., and Ph.D. in engineering from Hokkaido University in 2004, 2006, and 2009. He studied single crystal growth and scintillation properties of Ce-doped gadolinium pyrosilicate. He joined the Advanced Opto-electronics Device Research Group in NTT Photonics Laboratories in 2009, where he has been studying crystal growth of electro-optical materials, nonlinear optical devices, and diffractive optical elements for high-power lase machining.

Kaori Takayanagi
Engineer, Sustainable System Group, Zero Environmental Impact Research Project, NTT Space Environment and Energy Laboratories.
She received a B.E. in precision engineering and M.E. in environmental science from the University of Tokyo in 2018 and 2020. She studied recycling systems for building waste materials. She joined the Sustainable System Group in NTT Space Environment and Energy Laboratories in 2021, where she is engaged in research on waste-disposal system for asbestos-containing materials using laser.

Standardization Activities for Optical Fiber and Cable Technology in International Electrotechnical Commission

Yusuke Yamada, Taiji Sakamoto, Takashi Matsui, and Noriyuki Araki

Abstract

The International Electrotechnical Commission Technical Committee 86 (IEC TC 86) is an international standardization organization that prepares and decides on international standards in relation to products used for optical fiber telecommunication. In this article, we provide an overview of standardization activities, introduce topics discussed at the meetings in 2021 and 2022, and describe the Japanese standardization strategy in IEC TC 86.

Keywords: IEC, optical fiber, international standard

1. Introduction

The International Electrotechnical Commission (IEC) is a standardization organization that sets all of the required standards for electrical and electronics technologies. In IEC, Technical Committees (TCs), which are established for each technical field, hold detailed discussions on the content, publication, and revision of international standards, and TC 86 is in charge of specifications and test methods of optical products in optical communication systems. NTT is researching and developing technologies and requirements for optical communication systems, and international standards are closely related to equipment procurement and interconnection. Therefore, NTT is actively participating in IEC TC 86 standardization activities making proposals for international standardization, and involved in discussion of documents to guarantee the quality and interoperability of telecommunication networks and product specifications used in Japan. The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Study Group (SG) 15 is also discussing international standardization for optical fibers and cables from the viewpoint of requirements for public communication network systems, and we are actively participating in it. In IEC, standardization is mainly conducted from the viewpoint of consistency between procurement specifications for optical products and international standards, and in ITU-T, standardization is being discussed from the viewpoint of securing interoperability of communication systems and requirements. Standardization activities in IEC and ITU-T are being conducted in close cooperation with each other.

In IEC, TC 86 is in charge of fiber optics (optical fiber) technology, and its main purpose is to establish standards such as optical, environmental, and mechanical requirements of fiber optics products for optical communication systems, which are optical modules and devices used with optical fiber cables, connectors, and communication equipment. The technical fields of TC 86 are shown in **Fig. 1**, and the organizational structure of TC 86 is shown in **Fig. 2**.

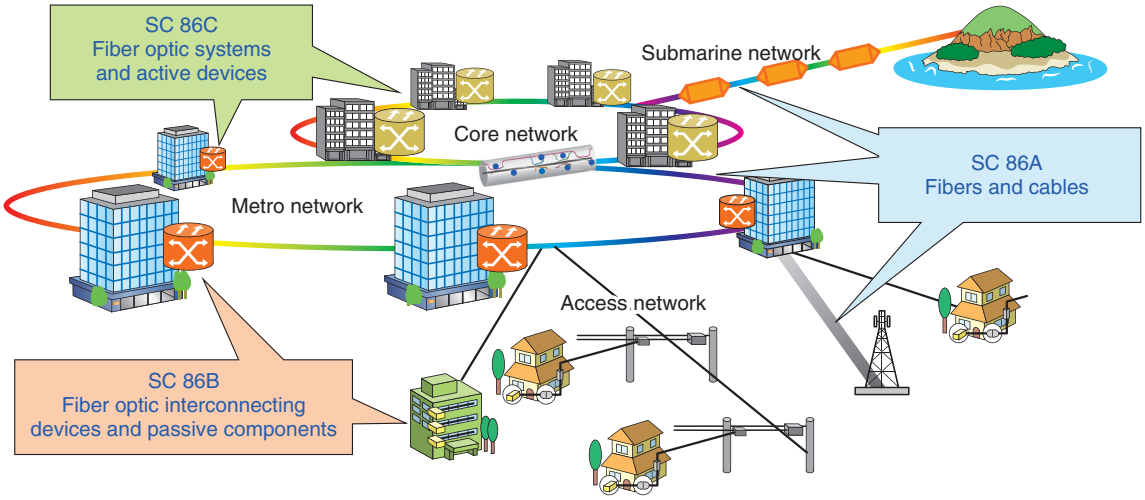


Fig. 1. Technical area of IEC TC 86.

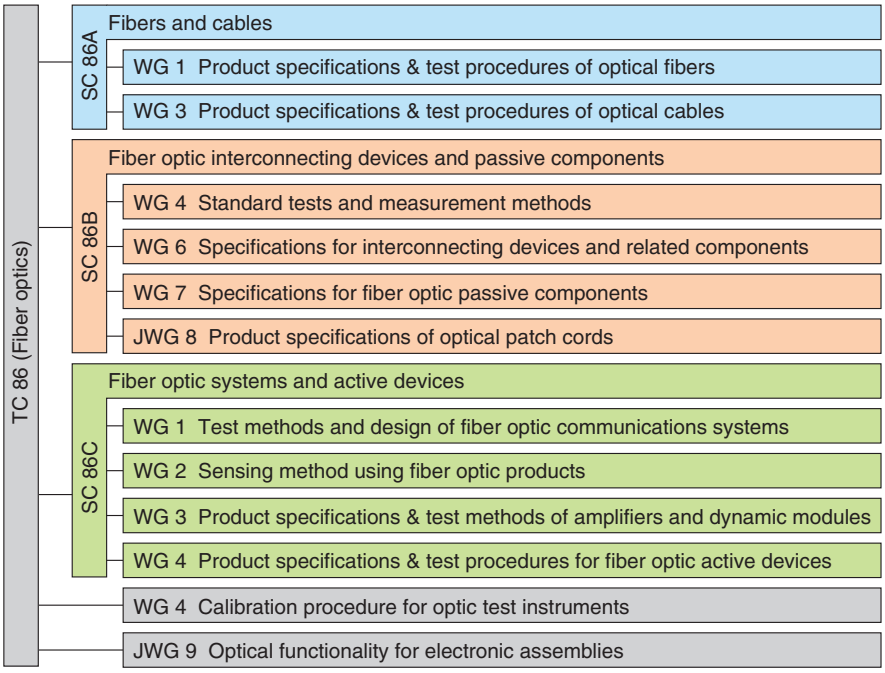
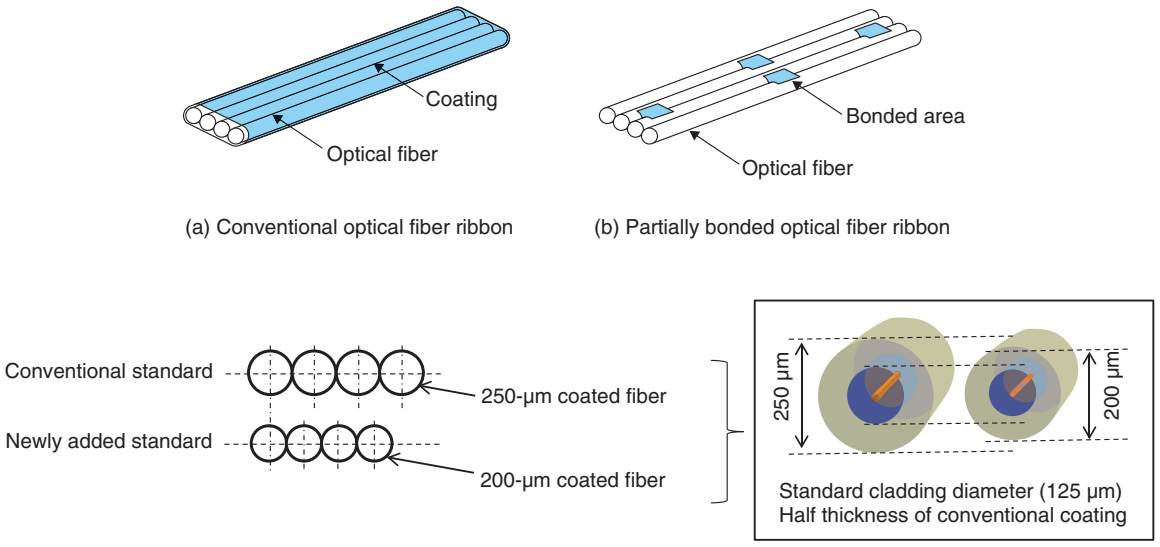


Fig. 2. SCs and WGs of IEC TC 86.

TC 86 has three Subcommittee (SCs) to make decisions in each technical field. SC 86A is in charge of optical fiber cables, SC 86B is in charge of optical connecting and passive devices, and SC 86C is in charge of optical subsystems and active devices. It also has 12 Working Groups (WGs) to discuss specific standards documents. Each WG proposes new or revised standards for the technical field it is in charge of and prepares documents, which are then issued and reviewed by each SC. This article describes recent trends in optical fiber and cable standards being discussed in IEC TC 86.



(a) Conventional optical fiber ribbon (b) Partially bonded optical fiber ribbon

(c) Configuration of optical fiber ribbon with 200-µm coated optical fiber

Fig. 3. Configuration of optical fiber ribbon.

2. Recent trend in standardization for optical fibers and cables

In the field of fiber optics for IEC TC 86, discussions on the standardization of optical cables and connecting devices for access systems have been active, especially against the background of the rapid increase in demand for optical fiber cables in datacenters and the rapid spread of FTTH (fiber to the home) in Europe and emerging countries. At SC 86A, which handles optical fiber cable standards, revisions are being made to optical fiber and optical fiber ribbon standards in line with the increasing number and high density of optical cables, and proposals and discussions are being made on various testing methods for optical cables in consideration of the usage environment in each country.

The standardization of a partially bonded optical fiber ribbon, which was developed and used for ultra-high density optical cables in Japan, has been discussed. **Figure 3** shows the configuration of an optical fiber ribbon. A partially bonded optical fiber ribbon can be discretely bonded in the longitudinal direction to improve flexibility, such as being able to roll up or bend in any direction, and can be mass spliced. By using the partially bonded optical fiber ribbon, the optical fiber assembled density in the optical cable can be dramatically increased, and it is commercially used for optical fiber networks in Japan. In IEC, the standard document was newly established as a product standard of optical fiber ribbon (IEC 60794-1-31). It has recently been applied to ultra-high fiber-count optical cables for inter/intra data center networks. In ultra-high fiber-count optical cables, it is effective in reducing the coating diameter of the optical fiber ribbon to make it smaller and denser. In addition to the standard coating diameter of 250 µm, an alternative coating diameter of 200 µm has been standardized. By applying this to optical fiber ribbon, it is possible to reduce the diameter, increase the density, and improve connection efficiency. In view of the situation in which connection compatibility can be ensured by the progress of fusion-splicing technology corresponding to 200-µm coating, as shown in Fig. 3(c), the standard document was published as a product standard of optical fiber ribbon applying 200-µm coated optical fiber. For submarine optical fiber cables, it is necessary to increase the number of optical fibers as communication demand increases. We are also deliberating the application of 200-µm coating, which is an alternative coating diameter, to cut-off shifted fiber (IEC 60793-2-50: B-654. A, B, and C) used for submarine applications.

The standards of test methods for optical fiber cables are indispensable for proper characterization of optical fiber cables. **Figure 4** shows the numbering system of such test methods and the proposal for

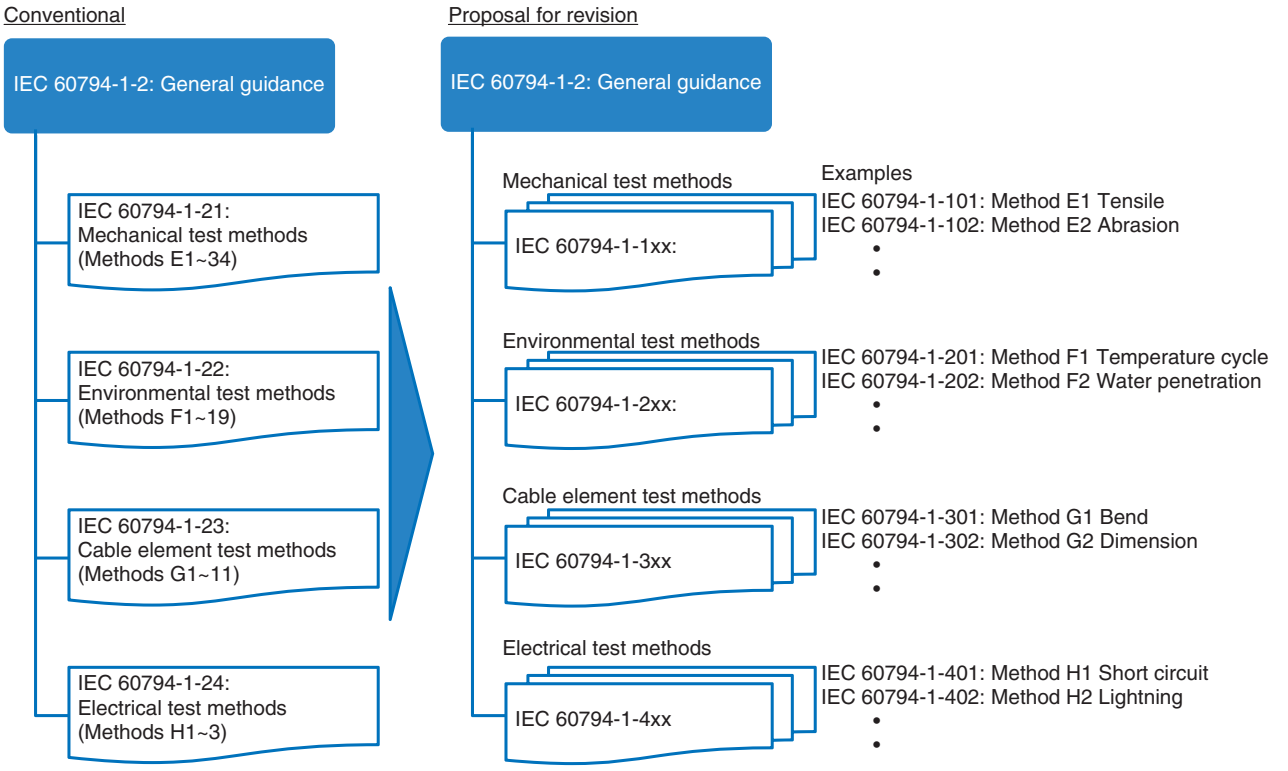


Fig. 4. Numbering system of test methods for optical fiber cables.

revision. A wide variety of test-method standards are divided into separate volumes to ensure timely maintenance of each standard. Japan proposed a test method for evaluating the freezing resistance of optical fiber cables considering their installation in cold regions on the basis of NTT's knowledge, and published it as a freezing test method (IEC 60794-1-215: Method E15C). Among the cable element test methods, Japanese experts are revising the document of the test methods for ribbon dimensions and geometry (IEC 60794-1-302: Method G2, IEC 60794-1-303: Method G3) and the test method for ribbon tear (separability) (IEC 60794-1-305: Method G5), which are closely related to the product standards for optical fiber ribbon, and deliberations are underway to make them appropriate test-method standards.

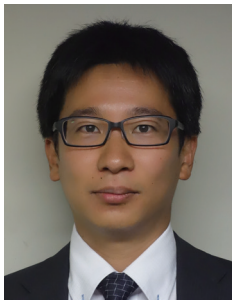
In the research and development (R&D) process, NTT conducts evaluation using these test methods to feedback to optical cable design and compatibility with the usage environment, and examines performance and reliability evaluation in practical application development of new products and expansion of application of developed products. Therefore, we are promoting the globalization of technologies developed by NTT and Japan through standardization activities in conjunction with R&D activities.

3. Further activities

Japan has aggressively promoted the domestic deployment of optical-fiber-cable technology, and has a strong presence as one of the major countries in IEC TC 86. On the basis of our extensive experience and knowledge in the introduction and operation of optical fiber and cable technologies, we will contribute to the development of international standards that contribute to the development of optical communication networks by closely cooperating with ITU-T, which is also involved in international standardization. We will also promote the establishment of next-generation optical fiber and cable technologies, which will be indispensable for IOWN (the Innovative Optical and Wireless Network), through both R&D and standardization activities.

Yusuke Yamada
Senior Research Engineer, Access Media Project, NTT Access Network Service Systems Laboratories.

He received a B.E. and M.E. in environmental system engineering from Nagaoka University of Technology, Niigata, in 2003 and 2005. In 2005, he joined NTT Access Network Service Systems Laboratories, where he has been engaged in research on optical fiber cable. He has contributed to the activity of IEC SC 86B in 2013–2014 and IEC SC 86A since 2017. He is a member of the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan. He received the best paper award at 12th OECC/IOOC in 2007.



Taiji Sakamoto
Distinguished Researcher, NTT Access Network Service Systems Laboratories.

He received a B.E., M.E., and Ph.D. in electrical engineering from Osaka Prefecture University in 2004, 2006, and 2012. In 2006, he joined NTT Access Network Service Systems Laboratories, where he has been engaged in research on optical fiber nonlinear effects, low nonlinear optical fiber, few-mode fiber, and multi-core fiber for optical multiple-input-multiple-output transmission systems. He is a member of Optica and IEICE.

Takashi Matsui
Distinguished Researcher, NTT Access Network Service Systems Laboratories.

He received a B.E., M.E., and Ph.D. in electronic engineering from Hokkaido University in 2001, 2003, and 2008. He attained the status of Professional Engineer (P.E.Jp) in electrical and electronic engineering in 2009. In 2003, he joined NTT Access Network Service Systems Laboratories, where he has been researching optical fiber design techniques. He has been contributing to the activities of IEC TC 86 (fiber optic systems) as an expert of SC 86A/WG1 and WG3 since 2009 and has been contributing to standardization efforts in ITU-T SG15 since 2022. He is a member of IEICE.

Noriyuki Araki
Director, Standardization Office, Research and Development Planning Department, NTT.

He received a B.E. and M.E. in electrical and electronic engineering from Sophia University, Tokyo, in 1993 and 1995. He joined NTT Access Network Service Systems Laboratories in 1995, where he researched and developed operation and maintenance systems for optical-fiber-cable networks. He has been contributing to standardization efforts in ITU-T SG6 since 2006. He was the rapporteur of Question 6 of ITU-T SG6 from 2006 to 2008 and rapporteur of Question 17 of ITU-T SG15 from 2008 to 2012. He also served as the chairman of the ITU-T Focus Group on Disaster Relief Systems and Network Resilience and Recovery. He was the vice-chairman of ITU-T SG15 from 2013 to 2022. He also contributes to the activities of IEC TC 86 (fiber optic systems). He received the ITU-AJ award from the ITU Association of Japan in 2017. He is a member of IEICE.

Case Study of Audible Noise on Analog Leased Lines Caused by Electromagnetic Disturbance

Technical Assistance and Support Center, NTT EAST

Abstract

If electromagnetic disturbances, which are generated from malfunctioning appliances or radio waves, interfere with metallic cables, it can cause telecommunication failures such as audible noise being heard when using telephones and disconnection of digital subscriber lines. This article provides a case study of audible noise interfering with voice-based services, the cause of the electromagnetic disturbances, and a countermeasure against them. This is the seventy-second article in a series on telecommunication technologies.

Keywords: electromagnetic disturbance, PBX, Noise Search Tester

1. Introduction

If electromagnetic disturbances generated from malfunctioning appliances or radio waves interfere with metallic cables, they can cause telecommunication failures such as audible noise being heard when using telephones, disconnection of digital subscriber lines, and transmission errors on ISDN (integrated services digital network) lines. To resolve such failures, it is necessary to identify the source of the electromagnetic disturbances and eliminate them. This article provides a case study of audible noise interfering with voice-based services, the cause of the electromagnetic disturbances, and a countermeasure against them.

2. Case study

A customer using a 3.4k analog leased line reported that a high-pitched audible noise could be heard when using certain telephones. Though the local telecommunication maintenance personnel applied countermeasures, including changing the line number; the audible noise was not cleared. Therefore, the Technical Assistance and Support Center (TASC), NTT EAST was asked to investigate the problem.

2.1 Configuration of equipment and failure state

The customer operates their own private branch exchange (PBX) and uses 3.4k analog leased lines between the PBX in the customer's main building and several offices located in the same city or surrounding areas, for extension calls. The configuration of the equipment is shown in **Fig. 1**. A redundant configuration is adopted between the customer's main building (in which the customer's PBX is installed) and an NTT building (telecommunication central office), having two different telecommunication access routes in the overhead section, so that the 3.4k analog leased lines can be maintained even in the event of a cable failure in the access network section. The route can be switched by changing the jumper cable in the main distribution frame (MDF) in the customer's main building. There are two routes between the NTT building connecting to the customer's main building and customer's offices: (1) a route turning at the MDF

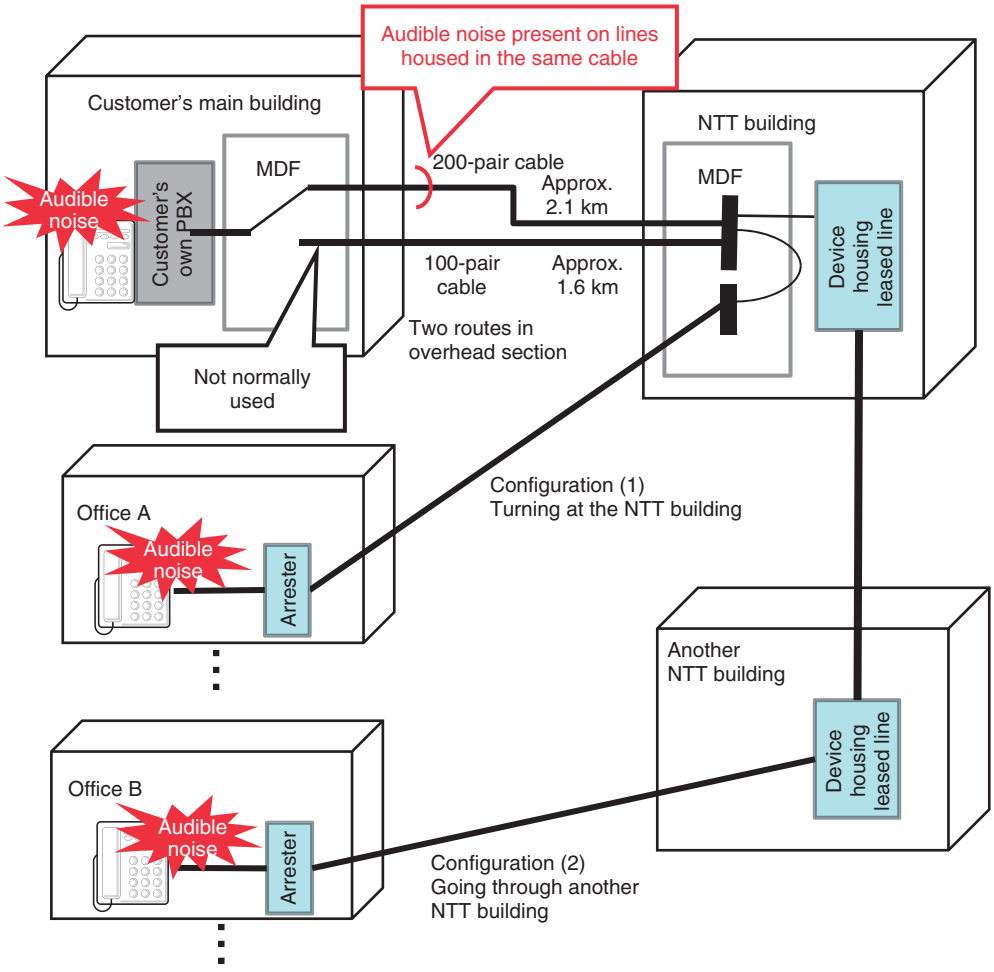


Fig. 1. Configuration of equipment.

in the NTT building and (2) one going through another NTT building in the city.

The customer reported that high-pitched audible noise was being constantly heard through the telephones installed at multiple offices. The results of on-site interviews with the customer revealed that the audible noise was present on four lines.

To confirm the details of the noise, on-site telecommunication maintenance personnel investigated all 300 lines installed in the customer's main building using a cable tester, and it was confirmed that the audible noise was present on 17 lines of the 200-pair cable in use. No audible noise was generated on lines of the other 100-pair cable. As a countermeasure, the telecommunication maintenance personnel changed a line number within the same 200-pair cable, but the audible noise was not cleared, so the cable was switched to the stand-by 100-pair cable in the redundant configuration, and the audible noise was cleared. Because the cause of the audible noise was unknown, and the audible noise was generated again when the route was switched back to the 200-pair cable due to connection failure, etc., TASC was asked to investigate the cause of the audible noise.

2.2 Investigation of the cause of audible noise

TASC first investigated the cause of the audible noise. TASC asked the on-site telecommunication maintenance personnel to check the condition of the equipment and measure the audible noise at the site. On the basis of the results obtained on-site, TASC analyzed the measurement results, determined the cause of the noise from the analysis results, and proposed a countermeasure.

(1) Confirmation of frequency characteristics and cycle of the audible noise

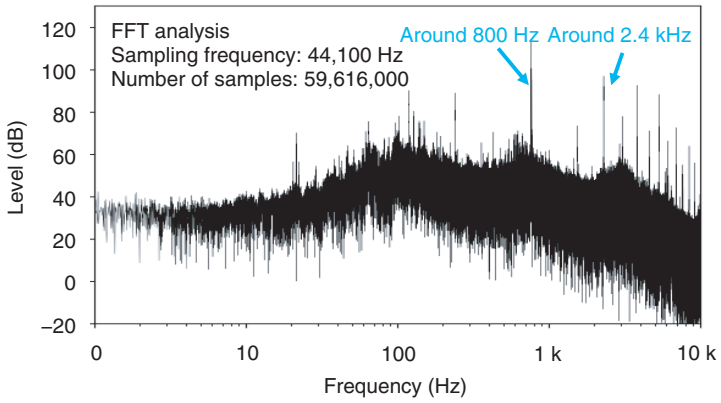


Fig. 2. Results of FFT analysis.

To confirm the frequency characteristics of the audible noise reported by the customer, it was recorded at the site. The recorded sound files were subjected to First Fourier Transform (FFT) analysis by TASC. The results of this analysis are shown in **Fig. 2**. It was found that the level of the noise signal was higher at the fundamental frequency (which is approximately 800 Hz) and its harmonics at odd multiples. It was also found that the audible noise was occurring periodically (every 20 to 30 s).

(2) Identification of noise source

To identify the lines with the highest audible noise, the voltage levels of the audible noise on 17 lines of the 200-pair cable routed into the customer's main building were measured. The Noise Search Tester (3144) and its probe, i.e., a voltage sensor (9741), both manufactured by Hioki E.E. Corporation (**Photo 1**), were applied to measure the common-mode voltage levels of the audible noise at the MDF of the NTT building. The basic specifications of the Noise Search Tester are listed in **Table 1**. Common-mode voltage levels for seven frequency ranges can be displayed by the tester's bar indicator.

The measurement results of the lines with the highest common-mode voltage level are shown in **Fig. 3**. It was found that the highest common-mode voltage level (about –2 dBV) occurred in the 1 kHz band, i.e., voltage level at frequencies between 500 Hz and 1.5 kHz.

Since this frequency range includes 800 Hz, i.e., the fundamental frequency of the recorded sound file, TASC concluded that it corresponds to the common-mode voltage level of the audible noise reported by the customer. It was also found that the common-mode voltage level fluctuates periodically and corresponds to the phenomenon observed by playing back the sound file, i.e., a high-pitched noise (at approximately 800 Hz) occurring periodically every 20 to 30 s.

Photo 1. Noise Search Tester 3144 (right) and voltage sensor 9741 (left).

2.3 Estimation of source of audible noise

The repetition of the sound at approximately 800 Hz suggests the "howler (off-the-hook) tone" of the PBX. A howler tone is an audible sound transmitted when a telephone is off the hook for an extended period, even though the line is not used. We examined the conditions under which the customer's PBX transmits a howler tone (**Table 2**) and found that the frequency, transmission time, and repetitive transmission conditions of the howler tones were almost identical to those of the audible noise identified in the investigation.

Since the PBX in question transmits a howler tone

Table 1. Basic specifications of Noise Search Tester.

Input terminal	• Dedicated terminal 9741 • BNC terminal
Maximum input voltage	5 V peak
Measurement range	• ×1 range: 0 to –30 dBV • ×10 range: –20 to –50 dBV
Frequency bandwidth	• 100 Hz to 30 MHz, separated into seven bands
Measurement-range setting and measurement-frequency bandwidth (–3 dB) (Measuring range: frequency bandwidth)	• 1 kHz: 500 Hz to 3 kHz • 15 kHz: 7.5 kHz to 22.5 kHz • 70 kHz: 5 kHz to 105 kHz • 250 kHz: 125 kHz to 375 kHz • 1 MHz: 0.5 MHz to 1.5 MHz • 3 MHz: 1.5 MHz to 4.5 MHz • 20 MHz: 10 MHz to 30 MHz

BNC: Bayonet Neill-Concelman

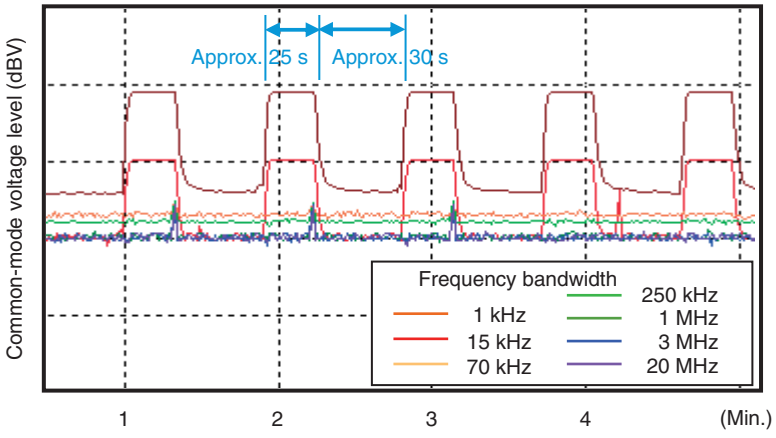


Fig. 3. Measurement results of common-mode voltage levels of audible noise using Noise Search Tester.

Table 2. Conditions for transmitting howler tone.

Howler tone	Frequency: 800 Hz Level: Max. +23 dBm (approx. 11 V)
Conditions	Detection of loop current of 13 mA or more
Howler-tone settings	Transmission for 30 s (repeated howler tones can be transmitted)

when it detects a loop current of 13 mA or more, the cause of the audible noise is assumed to be faulty insulation on the line connected to the PBX. The cause of the audible noise on multiple lines is assumed due to the deterioration of the balance of the line due to faulty insulation of the line, which induced the howler tone being sent to the line in question to be directed to an adjacent line.

2.4 Verification of countermeasure and its effectiveness

The line with the highest audible noise was a stand-by line that had been taken out of service due to the reconstruction of office B, but the jumper cable in the NTT building had been left connected. When the stand-by line connected to the MDF in the NTT building was disconnected, the audible noise on

multiple lines was eliminated.

3. Concluding remarks

A case study of audible noise on a 3.4k analog line and the countermeasure against it were introduced. The local maintenance personnel confirmed the details of the equipment configuration, recorded the audible noise in the customer's environment, and measured the voltage levels of the audible noise to identify its mechanism. The measurement results were analyzed at TASC, and a countermeasure based on the results was applied to clear the audible noise.

TASC would like to thank the local maintenance personnel for their cooperation.

The EMC Engineering Group in TASC continues to actively engage in technical cooperation, development, and dissemination of its technology through activities such as technical seminars to reduce telecommunication failures caused by electromagnetic disturbances, radio waves, induction, lightning, and other factors and to improve the reliability of telecommunication services.

External Awards

Honorable Mention Award
Winners: Hiroki Koyama, Chiba Institute of Technology; Yuuna Nakagawa, Chiba Institute of Technology; Shigeaki Tanimoto, Chiba Institute of Technology; Teruo Endo, Osaka Shoin Women's University; Takashi Hatashima, NTT Social Informatics Laboratories; and Atsushi Kanai, Hosei University
Date: July 2, 2022
Organization: International Institute of Applied Informatics (IIAI)

For "A Study of Risk Assessment Quantification for Secure Telework."
Published as: H. Koyama, Y. Nakagawa, S. Tanimoto, T. Endo, T. Hatashima, and A. Kanai, "A Study of Risk Assessment Quantification for Secure Telework," Proc. of the 12th International Congress on Advanced Applied Informatics (IIAI-AAI 2022), pp. 574–580, Kanazawa, Japan, July 2022.

Best Paper Award
Winners: Wataru Kobayashi, NTT Device Technology Laboratories; Shigeru Kanazawa, NTT Device Innovation Center; Takahiko Shindo, NTT Device Innovation Center; Manabu Mitsuhara, NTT Device Technology Laboratories; Fumito Nakajima, NTT Device Technology Laboratories
Date: July 6, 2022
Organization: The 27th OptoElectronics and Communications Congerence (OECC 2022)

For "1.5 pJ/bit, 128 Gb/s, 50°C Operation of AXEL for Short Reach Application."
Published as: W. Kobayashi, S. Kanazawa, T. Shindo, M. Mitsuhara, and F. Nakajima, "1.5 pJ/bit, 128 Gb/s, 50°C Operation of AXEL for Short Reach Application," OECC 2022, WD1-2, Toyama, Japan, July 2022.

Best Paper Award
Winners: Tomoyuki Kato, Fujitsu Ltd.; Hidenobu Muranaka, Fujitsu Ltd.; Yu Tanaka, Fujitsu Ltd.; Yuichi Akiyama, Fujitsu Ltd.; Takeshi Hoshida, Fujitsu Ltd.; Shimpei Shimizu, NTT Network Innovation Laboratories; Takayuki Kobayashi, NTT Network Innovation Laboratories; Takushi Kazama, NTT Network Innovation Laboratories/NTT Device Technology Laboratories; Takeshi Umeki, NTT Network Innovation Laboratories/NTT Device Technology Laboratories; Kei Watanabe, NTT Network Innovation Laboratories/NTT Device Technology Laboratories; Yutaka Miyamoto, NTT Network Innovation Laboratories
Date: July 13, 2022
Organization: OECC 2022

For "WDM Transmission in S-band Using PPLN-based Wavelength Converters and 400-Gb/s C-band Real-time Transceivers."
Published as: T. Kato, H. Muranaka, Y. Tanaka, Y. Akiyama, T. Hoshida, S. Shimizu, T. Kobayashi, T. Kazama, T. Umeki, K. Watanabe, and Y. Miyamoto, "WDM Transmission in S-band Using PPLN-based Wavelength Converters and 400-Gb/s C-band Real-time Transceivers," OECC 2022, WA3-4, Toyama, Japan, July 2022.

Young Researcher Award
Winner: Tatsuya Iizuka, NTT Space Environment and Energy Laboratories
Date: July 15, 2022
Organization: Information Processing Society of Japan (IPSJ)

For "Corner-reflector-based Chipless RFID for Wide Range Readout with Low Power Millimeter Wave Radar."
Published as: T. Iizuka, T. Sasatani, N. Kosaka, M. Hisada, K. Narumi, and Y. Kawahara, "Corner-reflector-based Chipless RFID for Wide Range Readout with Low Power Millimeter Wave Radar," Proc. of Multimedia, Distributed, Cooperative, and Mobile Symposium (DICOMO) 2022, 5H-3, pp. 1085–1091, July 2022.

IPSJ Yamashita SIG Research Award
Winner: Toshiki Shibahara, NTT Social Informatics Laboratories
Date: July 29, 2022
Organization: IPSJ

For "Privacy Risk of Differentially Private Bayesian Neural Network."
Published as: T. Shibahara, T. Miura, M. Kii, and A. Ichikawa, "Privacy Risk of Differentially Private Bayesian Neural Network," Proc. of Computer Security Symposium 2021, pp. 245–252, Oct. 2021.

Best Paper Award
Winners: Xuejun Xu, NTT Basic Research Laboratories; Masaya Hiraishi, University of Otago; Tomohiro Inaba, NTT Basic Research Laboratories; Tai Tsuchizawa, National Institute of Advanced Industrial Science and Technology; Atsushi Ishizawa, Nihon University; Haruki Sanada, NTT Basic Research Laboratories; Takehiko Tawara, Nihon University; Jevon Longdell, University of Otago; Katsuya Oguri, NTT Basic Research Laboratories; and Hideki Gotoh, NTT Basic Research Laboratories/Hiroshima University
Date: August 3, 2022
Organization: The 15th Conference on Laser and Electro-Optics Pacific Rim (CLEO-PR 2022)

For "Erbium-doped Rare-Earth Oxide Thin Film Waveguides for Integrated Quantum Photonic Devices."
Published as: X. Xu, M. Hiraishi, T. Inaba, T. Tsuchizawa, A. Ishizawa, H. Sanada, T. Tawara, J. Longdell, K. Oguri, and H. Gotoh, "Erbium-doped Rare-Earth Oxide Thin Film Waveguides for Integrated Quantum Photonic Devices," CLEO-PR 2022, July/August 2022.

Oral Talks Award
Winner: Motoki Asano, NTT Basic Research Laboratories
Date: August 11, 2022
Organization: The 18th International Workshop on Nanomechanical Sensing (NMC2022)

For "An Optomechanical Prober in Liquid with Twin Microbottle Resonators."
Published as: M. Asano, H. Yamaguchi, and H. Okamoto, "An Optomechanical Prober in Liquid with Twin Microbottle Resonators," NMC2022, Aug. 2022.