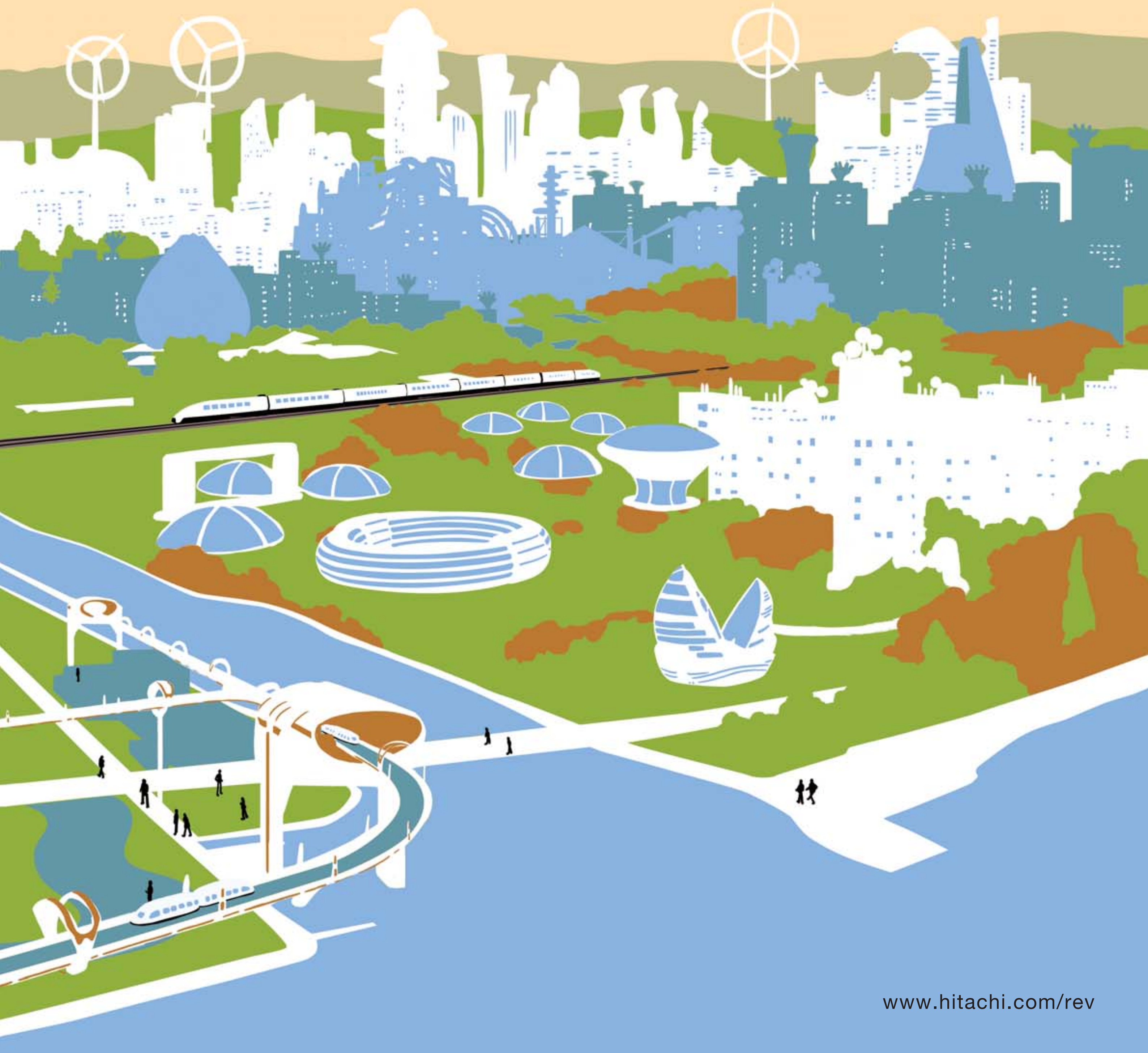
Hitachi Review
Volume 64 Number 8 November 2015

HITACHI
Inspire the Next

Innovative R&D Report 2015



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Preface

While rapidly progressing globalization is encouraging vibrant interaction and movement among people and goods, the challenges facing society are becoming increasingly complex and diverse, including how to deal with environmental and resource problems and how to protect against various different threats. Through our Social Innovation Business, which combines advanced information technology (IT) with a variety of infrastructure technologies, Hitachi is seeking to offer solutions to these mounting challenges. In April 2015, Hitachi introduced a major restructuring of its research and development (R&D) organization to enhance its capacity for delivering solutions to societal challenges. The new organization for conducting customer-oriented global R&D is based on three strategies.

The first is “collaborative creation with customers.” This involves seeking to develop genuine solutions while working with customers to sketch out desirable scenarios for the future and to uncover latent needs. At four centers around the world, in Tokyo, North America, China, and Europe, we are utilizing proprietary service design methods to identify challenges and solve them.

This is underpinned by the second strategy of “technology innovation.” The diversity of Hitachi’s businesses and products means that we have accumulated technologies and other know-how from a wide range of fields. Along with enhancing and further developing our specific technologies in the fields of Energy, Electronics, Mechanical Engineering, Materials, Systems Engineering, Information and Telecommunications, Controls, Production Engineering, and Healthcare, we are laying the foundations for the creation of new value through the organic fusion of these ingredients.

Furthermore, anyone involved in research should never forget that their fundamental role is to look toward the future with a long-term perspective. The third strategy of “exploratory research” is the embodiment of this fundamental purpose of R&D. With a focus on the four fields of physical sciences, life sciences, information sciences, and “frontier,” R&D at Hitachi is preparing the ground for open innovation while also adopting a free-thinking approach to pioneering new fields.

This issue of *Hitachi Review* presents examples of the major solutions and research work undertaken in accordance with this new R&D organizational structure and strategy. I hope these articles will help you become more familiar with what we are doing here at Hitachi.

Keiji Kojima

Vice President and Executive Officer,
CTO, and General Manager of Research & Development Group
Hitachi, Ltd.

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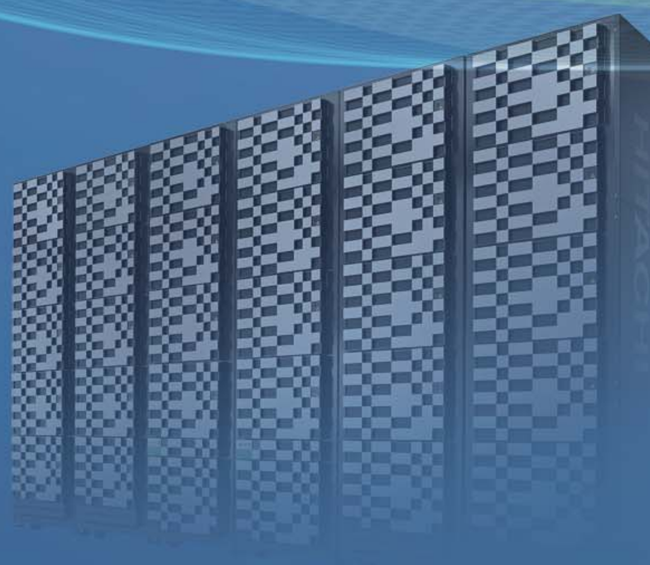


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Frontier Topics
Leading Technology Developments from Hitachi

Hitachi is developing a variety of solutions and technologies based on its strategies of "collaborative creation with customers," "technology innovation," and "exploratory research."
This article highlights some notable developments from recent major achievements.

Collaborative Creation with Customers

JR East app screens

Content for JR East App

Hitachi has collaborated with the East Japan Railway Company (JR East) on the development of content for the JR East app, an initiative introduced by the company to improve service quality. This app features a wide range of content relating to railway services, providing comprehensive service status to allow users to view at a glance. It also provides realtime information on train locations, including any delays, and a realtime timetable that lists the train departure times updated at stations. Designed for use on a smartphone, the app naturally supports the usual tap and swipe user interface, and the content has been developed for ease-of-use, including condensing information to enable a quick overview of service status on a small screen while still ensuring the full details are available on separate screens. As of May 2015, the app had been downloaded more than 1.2 million times since its release in March 2014.

NEXPERIENCE / Cyber-Proof of Concept (Cyber-PoC) for Collaborative Creation with Customers

NEXPERIENCE / Cyber-PoC is an information technology (IT) tool for creating and designing innovative business model from the customer's perspective. This tool is capable of visualizing data while assessing the value of designed solutions through big data analytics. The uniqueness of this IT tool is that it has integrated the analytics technologies and the collaborative creation methodologies that are cultivated by Hitachi from diversified industries over many years. Its purpose is to accelerate collaborative creation with customers through simulating impacts and calculating Return of Investment on the designed solutions. For example, if a city is planning to relieve traffic congestion by implementing an underground train system, NEXPERIENCE / Cyber-PoC can be used to visualize the mitigation impacts from installing railway lines and stations, to predict the profitability for investment, and to validate operations and cost calculation based on data. Currently, NEXPERIENCE / Cyber-PoC has been applied to the railway projects and the chemical plant for productivity analysis. Hitachi will extend its application to the fields of energy and healthcare.

NEXPERIENCE / Cyber-PoC demonstrations

Technology Innovation

ARIETTA 70/60 Diagnostic Ultrasound System

Released in April 2014, the ARIETTA* 70/60 diagnostic ultrasound system was the first to be sold under the brand of Hitachi Aloka Medical, Ltd. A feature of the system is a novel signal processing technique for high image quality developed by drawing on the comprehensive capabilities of Hitachi. The technology enhances the performance of all of the modules (probe, frontend, beam former, backend, and monitor) from receiving the ultrasound signal of the body being scanned all the way to displaying the image. It also enhances image quality by optimizing signal transmission from one module to another. The beam former module in particular includes a new phasing application-specific integrated circuit (ASIC) for forming the ultrasound beam that is so critical to image quality. This helps improve both the spatial and time resolution. The system includes a range of applications to suit different user needs, including the automated region-setting function for obstetrics that makes it simple to obtain a clear three-dimensional image of a fetus, and the contrast-imaging function for radiology that assesses blood flow in liver tumors.

* ARIETTA is a trademark of Hitachi Aloka Medical, Ltd.

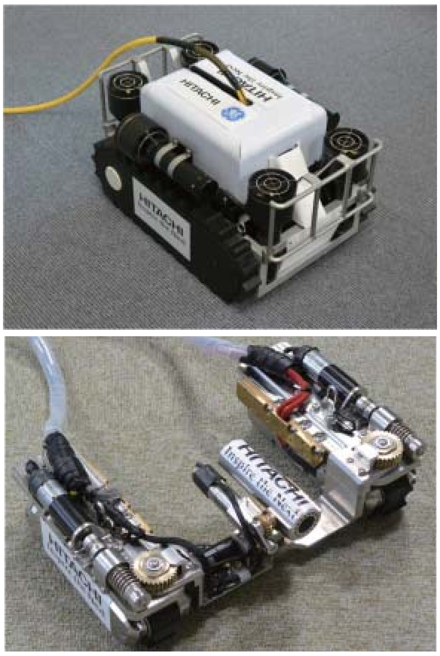
ARIETTA 70/60 diagnostic ultrasound system and display image

High-end and Mid-range Storage

Hitachi Virtual Storage Platform G1000 (left) and G800 (right)

Along with growing use of big data to create new value, the storage systems that provide the underlying platforms need scalability and ease-of-operation in order to respond rapidly to business growth and changing strategies. The high-end G1000 model of Hitachi Virtual Storage Platform uses global virtualization, a virtualization technology that enables multiple storage devices to appear as a single device, allowing migration of storage hardware without interrupting applications, and rapid system recovery in the event of a disaster. This makes storage systems easier to manage by improving storage system operation and continuity of data access. Furthermore, because all models, from high-end to mid-range, run the same platform software, the mid-range models can take advantage of the same advanced functions as the G1000, including its storage virtualization technology. This gives Hitachi Virtual Storage Platform the ability to scale easily with business growth by upgrading to more advanced models without the need for changes to operation and management practices.

Frontier Topics Leading Technology Developments from Hitachi



Underwater swimming robot for surveying the Fukushima Daiichi Nuclear Power Station (top) and shape changing robot (bottom)

Survey Robot for Fukushima Daiichi Nuclear Power Station

Cooling water continues to be supplied to the pressure vessel during the recovery work following the accident at Fukushima Daiichi Nuclear Power Station, and some of this water has leaked into the power plant and collected in a heavily contaminated form. To minimize the quantity of this retained water, it is necessary to identify and plug these leaks. To achieve this, Hitachi, Ltd. and Hitachi-GE Nuclear Energy, Ltd. have developed an underwater swimming robot and shape changing robot to look for these cooling water leaks, survey the condition of the fuel, and so on. In addition to moving along the bottom, the underwater swimming robot is also equipped with the ability to swim around obstacles and then re-orient and attach itself to a wall so that it can continue on its way. The shape changing robot, meanwhile, can reconfigure itself to pass through confined spaces, giving it the ability to move reliably both over uneven surfaces and through pipes with diameters as small as 100 mm. Through a project sponsored by the Agency for Natural Resources and Energy, the intention is to use the robots for survey work in the lead-up to the removal of fuel from Fukushima Daiichi Nuclear Power Station.

Autonomous Haulage System for Mining Dump Trucks

Hitachi Construction Machinery Co., Ltd. is working on the development of autonomous haulage system for mining dump trucks, with site trials commencing in 2013. This autonomous haulage system uses communication technology to interconnect management systems with onboard vehicle control systems and enable mine site operations such as driving and unloading to be performed by driverless vehicles. To improve the efficiency of mining operations, there is strong demand in the mining industry for ways of ensuring that safety and productivity are maintained at a high level despite the harsh conditions present at mine sites. The autonomous operation of driverless dump trucks is recognized as one way of fulfilling this need. In March and April 2015, Hitachi Construction Machinery conducted an operational demonstration of autonomous haulage dump trucks for major mining companies at a proving ground in Australia. Hitachi intends to continue developing this function with a view to practical applications.

Autonomous haulage mining dump truck

Energy-saving Home Appliances

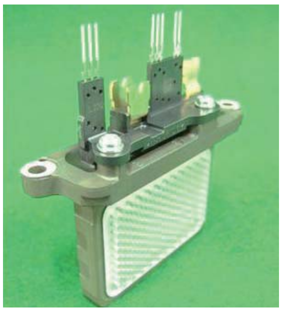
Hitachi has long been working on ways of making home appliances more energy efficient. Accompanying this have been product developments aimed at adding unique technology. The vacuum compartment series of large-capacity refrigerators feature a new function that keeps vegetables nutritious and crisp, and the performance of the vacuum compartment that uses the power of vacuum to maintain freshness in meat and seafood has been enhanced compared to previous models. Room air conditioners, meanwhile, use the multi-monitoring system, which tracks and controls air flow to warm users' feet in the winter and keep the entire room cool during the summer. The natural refrigerant heat-pump water heater for home use features enhanced energy efficiency from use of the industry-first* hot water storage unit with a urethane foam-filled heat insulation structure. In the FY2014 product and business model categories of the Grand Prizes for Excellence in Energy Efficiency and Conservation awards, the room air conditioners (RAS-X40E2 and 14 other models) won the METI Minister's Prize, and the natural refrigerant heat-pump water heater for home use models that use the urethane-insulated storage unit (BHP-FV46PD and 74 other models) won the Chairman's Prize, the Energy Conservation Center, Japan.

Large-capacity refrigerator

Room air conditioner

Natural refrigerant heat-pump water heater for home use

* As of the product launch date on October 20, 2014. Refers to the hot water storage unit in natural refrigerant heat-pump water heater for home use models for the Japanese market. Based on research by Hitachi Appliances, Inc.



Direct water-cooled power module with double-sided cooling (top) and third-generation inverter (bottom)

Compact Inverter with High Output Power

The accelerating adoption of hybrid and other electric vehicles is taking place against a background of increasingly stringent environmental regulation of automobiles throughout the world. Complying with tight environmental standards requires improvement in the efficiency of electric powertrains, including a reduction in their power consumption, and this in turn requires shrinking the size and boosting the output of inverters and other components. A third-generation inverter designed for small size and high output has made significant improvements in cooling performance through the use of newly developed power modules with direct water-cooling that cool both sides of the semiconductor, as opposed to only one side in earlier designs. The inverter also features a proprietary design that immerses the power module in cooling water. Daimler AG is actively working on the development of electric vehicles. Recognizing the features of this new inverter that combines small size and high output, Daimler has selected it for use in the first plug-in hybrids to appear under the Mercedes-Benz brand.

Frontier Topics Leading Technology Developments from Hitachi

Artist's impression of completed Guangzhou CTF Finance Centre to which Hitachi has supplied ultra-high-speed (1,200 m/min) elevators (left) and new 2,200-kVA control unit (right)

Ultra-high-speed Elevator

Hitachi, Ltd. and Hitachi Elevator (China) Co., Ltd. have supplied ultra-high-speed elevators to the Guangzhou CTF Finance Centre, a high-rise building (height: 530 m) in Guangzhou, China that is scheduled to open in 2016. These ultra-high-speed elevators are the fastest in the world* (1,200 m/min), able to travel the 440 m up to the 95th floor in approximately 43 s. This world-leading speed was achieved through the development of a variety of new drive and control technologies, including a permanent magnet motor that combines high output with a slim profile and a rope that is stronger despite a smaller cross-section diameter, thereby reducing the load on the traction machine and enabling it to be made smaller. The elevator successfully combines ultra-high speed with safety and comfort through the use of a governor and an emergency stop brake, and the adoption of techniques for decreasing car vibration and reducing the sensation of ear blockage.

* As of June 2015

Container-type Energy Storage System

Along with growing use of photovoltaic and wind power generation, there are concerns that the connection of large amounts of renewable energy capacity with variable output to the grid will lead to power system instability. In response, Hitachi has developed a 1-MW container-type energy storage system to help maintain grid stability by balancing supply and demand for electric power. The energy storage system features a long 10-year operating life and is provided in an all-in-one package that incorporates approximately 1,600 lithium-ion batteries into a container along with a control unit, power conditioner, and other components. Being containerized not only shortens lead times and reduces installation costs, it also enables large-capacity systems to be configured by adding additional containers. A demonstration project commenced in 2015 in New Jersey, USA where a frequency regulation market is already in place. Hitachi collects operational data to verify the value of energy storage systems in the frequency regulation market and to improve performance.

1-MW container-type energy storage system

Exploratory Research

Atomic-resolution Holography Electron Microscope

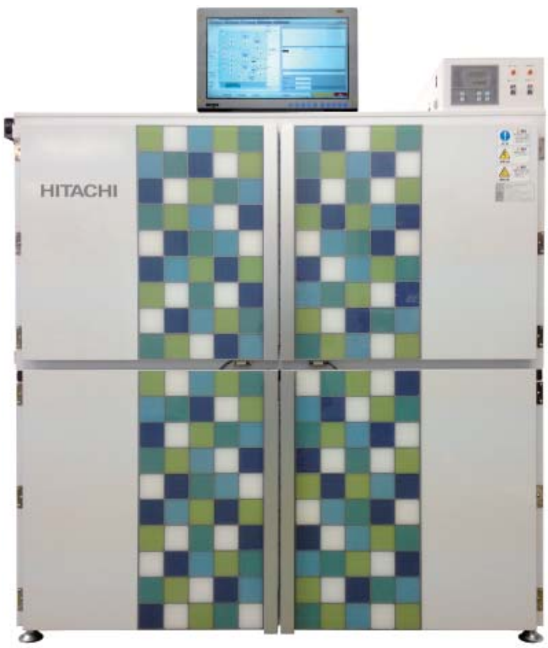
With the aim of developing materials with groundbreaking functions and properties, work is progressing on the development of techniques for atomic-resolution measurement of the internal electromagnetic fields that govern these material properties. The atomic-resolution holography electron microscope has been developed, with assistance from the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program), a national project. It is the world's first ultra-high-voltage electron microscope equipped with a spherical-aberration corrector. The highly stabilized electron microscope system enabled the equipping of the corrector. In this development, a number of new technologies (as follows) were successfully applied to improve the stability of the electron microscope system.

(1) A 1.2-MeV electron beam with suppressed energy dispersion, (2) an electron gun emitting high-brightness electron beams with long-term stability, (3) development of facility technologies to eliminate degradation factors of resolution

Performance testing succeeded in transmitting structural information from a crystal to a camera with a world-record resolution of 43 pm. Hitachi intends to use the microscope to help develop the new materials that will underpin a sustainable society by studying the quantum phenomena responsible for the functions of such things as magnets, batteries, and superconductors.

Atomic-resolution holography electron microscope

Automated Cell Culture System for Regenerative Medicine



Automated cell culture system for regenerative medicine

There are growing expectations for the potential of regenerative medicine to provide revolutionary new ways to cure diseases that are difficult to treat using conventional drugs or medical treatment. A major challenge to be overcome if regenerative medicine is to be more widely adopted is the development of techniques for the low-cost, bulk production of cells at the high quality levels needed for medical use. As part of its development of closed automated cell culture systems for regenerative medicine, Hitachi has conducted automated culturing experiments using human oral mucosal epithelial cell sheets to demonstrate the ability to produce regenerated tissue with a level of quality equivalent to manual methods. The newly developed system uses fully closed culture vessels and flow channels to prevent biological contamination by microorganisms from the external environment, opening up the potential for stable quality and bulk production at levels that would be impossible using existing manual methods. In addition to developing a technique for transporting cells in the closed culture vessels while maintaining their inner temperature, pressure, and sterility, Hitachi is also working on using the technology for the automated culturing of cell sheets for cornea regeneration and post-operative recovery after endoscopic submucosal dissection (ESD) by Tokyo Women's Medical University, which has clinical experience in this area.

Technotalk

New Global R&D Organization for Customer-oriented Innovations

Yukari Nagai, Ph.D. Dean and Professor of School of Knowledge Science, Japan Advanced Institute of Science and Technology (JAIST)
Norihiro Suzuki, Ph.D. General Manager, Global Center for Social Innovation, Research & Development Group, Hitachi, Ltd.
Yoshitaka Nishino, Ph.D. General Manager, Center for Technology Innovation, Research & Development Group, Hitachi, Ltd.
Kimiya Yamaashi, Dr. of Informatics Deputy General Manager, Center for Technology Innovation, Research & Development Group, Hitachi, Ltd.
Shinji Yamada, Ph.D. General Manager, Center for Exploratory Research, Research & Development Group, Hitachi, Ltd.

HITACHI undertook a major restructuring of its R&D organization in April 2015 to create a structure based on three innovation models that would facilitate the operation of its Social Innovation Business, which uses a fusion of infrastructure technology and IT to overcome the challenges facing customers and other parts of society. This reorganization marks a switch from a "product out" to a "market in" model, and will strengthen R&D that targets innovations that go beyond the development of individual technologies. This will create a customer-oriented global R&D organization in which researchers work with customers on the collaborative creation of solutions underpinned by a wide range of technical fields and research resources.

Handling Collaborative Creation with Customer through Global Organization

Nagai: I am a Professor of the School of Knowledge Science, Japan Advanced Institute of Science and Technology (JAIST), specializing in subjects such as innovation design. With Hitachi having restructured its research and development (R&D) organization in April 2015, I would like to talk to you today about the reforms you are undertaking to generate innovation, while also touching on my own academic interests.

Hitachi has consolidated its R&D into three organizations, one of which is its Global Center for Social Innovation. Can you please explain the role of this organization?

Suzuki: In the recent organizational change, our research facilities in Japan and overseas were realigned under three different innovation models, namely collaborative creation with customers, technology innovation, and exploratory research. The Global Center for Social Innovation is the organization responsible for collaborative creation. We are the frontline research organization working with customers to identify challenges and seek solutions, and as the "Global" in our name indicates, we represent a global organization that includes the overseas research facilities. Collaborative creation with customers involves three steps. Firstly, we work with customers to identify areas in which they are being challenged and draw a shared vision towards which we will work by resolving issues. Next, we clarify the concept based on this vision and develop a prototype. The prototype is then tested for proof of concept at the customer site before taking it to market and creating a solution.

Nagai: While customer-oriented development is nothing new at Hitachi, I understand this is about formalizing this approach?

Suzuki: Yes, that is correct. The Design Division was the research organization responsible for usability assessment, ethnographic research and other methodologies based on social sciences to design products and services. The new Global Center for Social Innovation was formed by integrating the Design Division together with the research team working on service design at our Yokohama Research Laboratory and other research teams who were delivering technologies and solutions to customers. By assigning researchers with service design skills close to customers both in and outside of Japan, and by augmenting this with staff who understand and can propose technology, solution proposals through collaborative creation will be accelerated.

Nagai: Please tell me about your global strategy.

Suzuki: We are operating through four regional centers to capture region-specific needs: Tokyo (Asia-Pacific), North America, China and Europe. Each center will focus delivering solutions to regional challenges: North America, through advanced solutions based on big data analytics platforms; China, through solutions addressing new industrial policies in China such as new forms of urbanization and low-carbon society, and Europe, through solutions to common challenges facing a matured society such as aging infrastructure and decreasing population. Solution development will involve the regional centers integrating solutions according to the challenges and needs of their respective regions based on technology platforms developed by the Center for Technology Innovation. To achieve this, we are fortifying research related to service and solution design, and intend to support Social Innovation Business worldwide through collaborative creation with customers in each region.

Nagai: I recognize that developing scenarios of desirable futures is essential to achieving social innovation. How do you deal with this?

Suzuki: We intend to deploy service design techniques for collaborative creation such as the NEXPERIENCE / Opportunity Finding and vision design. The NEXPERIENCE / Opportunity Finding is a way of predicting societal trends by studying citizens in a particular country or region from the perspective politics, economics, society, and technology (PEST), and assess how peoples' values change by considering how these factors interact with each other as they change over time. These predictions provide a basis to develop and test revolutionary prototypes and deliver solutions, using the diverse technology platforms of the Center for Technology Innovation and the advanced technologies of the Center for Exploratory Research.

Seeking to Achieve Technology Innovation that Originates with Customers

Nagai: The role of the Center for Technology Innovation within Hitachi's new R&D organization is to deal with technology innovation. What will be its innovation strategy?

Nishino: The mission of the Center for Technology Innovation is to develop innovative products and services by combining different types of technology. To achieve this, we have restructured our overall organization along technology lines that transcend the boundaries between our previous research laboratories by establishing nine Centers for Technology Innovation to work in the fields of Energy, Electronics, Mechanical Engineering, Materials, Systems Engineering, Information and Telecommunications, Controls, Production Engineering, and Healthcare, respectively. Because the creation of innovative products in recent years has required the combination of technologies from various different fields, organizing along technology category lines rather than by laboratory helps facilitate this process. The key role of the Center for Technology Innovation is to deliver technology-oriented solutions by concentrating on specific fields to strengthen individual technologies. However, while they are technology-oriented, a key feature of the centers is that they do not adopt a "product out" approach, rather they deal primarily with technology innovation that originates with customers, while also deepening their relationship with the Global Center for Social Innovation, which acts as the customer-facing organization.

Nagai: Can you provide any examples of this combination of technologies?

Nishino: Development that matches customer needs, such as rolling stock that is not only fast but also provides high levels of ride comfort and safety, for example, invariably requires a combination of technologies. This includes the growing importance of open innovation, involving the incorporation of technologies, not just from within Hitachi, but also from external sources. For example, Hitachi supplies proton beam cancer therapy systems that utilize technologies for particle accelerators and beams. To develop these

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Dean and Professor of School of Knowledge Science, Japan Advanced Institute of Science and Technology (JAIST)

Master's degree (Fine Art) from Musashino Art University (1990), Ph.D. from Chiba University (2002), Ph.D. in Computer Science from University of Technology Sydney (2009). Currently head of the Center for Regional Innovation and professor at the Research Center for Innovative Lifestyle Design, JAIST. Specialties include innovation design theory and knowledge science.

Norihiro Suzuki, Ph.D.

General Manager, Global Center for Social Innovation, Research & Development Group, Hitachi, Ltd.

Joined Hitachi, Ltd. in 1986 as a researcher working in digital image signal processing and embedded systems. Dr. Suzuki has held various positions including head of the R&D Division of Hitachi America, Ltd., before being appointed to his current position in April 2015. Dr. Suzuki is a member of The Institute of Image Information and Television Engineers, IEICE and the IEEE.

further, we are working on R&D* that incorporates the realtime tumor tracking radiotherapy technique developed jointly with Hokkaido University and funded by the government's Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program).

Yamaashi: Various forms of new value have been created through the combination of different technologies or applications that cross multiple fields. One example is the contribution to dramatic advances in semiconductor technology made by the use in semiconductor testing systems of world-leading electron microscopes, a subject that Hitachi has been researching since as far back as the 1940s. We have also brought innovations to the medical field by using advanced image processing techniques developed for television in diagnostic ultrasound imaging systems to provide realtime, three-dimensional imaging of fetuses or of the heart, or other organs. We have also produced new solutions by using image processing techniques in such systems as those for security and for the remote monitoring of machinery operation. Having technical capabilities that cover a wide range of fields is one of Hitachi's strengths, and our aim is to draw on this strength to contribute to overcoming a greater number of societal challenges.

Formalizing Hitachi's Technology Portfolio so that it Can be Put to Use

Nagai: While the value of a technology comes about after going through a process of enhancement and refinement, there are many technologies that never make it to market. Nevertheless, extremely valuable technical knowledge is created in the process and built up over time. If this knowledge can be put to use satisfying new requirements, then new ways forward can be found. Such applications and fusions of technology represent a genuinely new approach to technology development.

Yamaashi: As advanced technology from one field should also have applications elsewhere, the key question becomes how to identify such pathways. The technology we develop is our wealth, and our aim is to deliver this wealth to as many customers as possible in ways that are of value to them.

Nishino: While Hitachi has been building up core technologies through the process of product development ever since the 5 HP induction motor we developed in 1910, these technologies have not always been organized into a formal structure. I believe that formalizing group technologies in the form of technology platforms as we are currently doing will not only make it easier to establish strategies for enhancing our technology from the perspective of a broad overview, it will also encourage the use of this technology.

Nagai: If idle technology can be put to use, we can expect to see a steady stream of new developments emerging synergistically. Establishing the capabilities to create a comfortable and prosperous society by putting together numerous requirements with their potential solutions will also make consumers like myself happy.

Suzuki: From the perspective of the Global Center for Social Innovation, organizing the technology platforms of the Center for Technology Innovation into a formal structure and making these visible to overseas R&D operations is of particular significance. I anticipate that this will lead to new discoveries as people realize that

* Utilizes the results of "Advanced Radiation Therapy Project: Real-time Tumor-tracking with Molecular Imaging Technique" program (Principal Investigator: Professor Hiroki Shirato of the Graduate School of Medicine, Hokkaido University), which ran from March 2010 to March 2014 under the Japanese Cabinet Office's FIRST Program.

Yoshitaka Nishino, Ph.D.

General Manager, Center for Technology Innovation, Research & Development Group, Hitachi, Ltd.

Joined Hitachi, Ltd. in 1985. After working on the development of nuclear power plants, water supply and sewage treatment technology, and control systems for chemical and pharmaceutical plants, and at the Technology Strategy Office, he was appointed to his current position in April 2015. Dr. Nishino is a member of The Japan Society of Mechanical Engineers (JSME), The Society of Chemical Engineers, Japan (SCEJ), the Society of Instrument and Control Engineers (SICE), and the Atomic Energy Society of Japan (AESJ).

Kimiya Yamaashi, Dr. of Informatics

Deputy General Manager, Center for Technology Innovation, Research & Development Group, Hitachi, Ltd.

Joined Hitachi, Ltd. in 1986. After working on R&D on human interfaces, ITS, and inverters, and holding positions that included Research Director at the Central Research Laboratory, he was appointed to his current position in April 2015. Dr. Yamaashi is a member of The Institute of Electrical Engineers of Japan (IEEJ) and the Information Processing Society of Japan (IPSJ).

particular technologies can be used to satisfy the needs of customers which vary by region.

Finding Solutions to Upcoming Challenges as a Means of Future Innovation

Nagai: I understand the role of the Center for Exploratory Research is to undertake exploratory research. Is this somehow different from the world of Advanced Research Laboratory?

Yamada: Basic research in the past has tended to focus on investigating one particular topic at a time. It was a leisurely approach. The Center for Exploratory Research, however, was established based on the idea that dealing with the most pressing issues facing global society demands an exploratory model of basic research that takes a more diverse and interactive approach to these challenges and to communicating its results. In terms of time frames, one point of difference from the Global Center for Social Innovation and Center for Technology Innovation is that the Center for Exploratory Research considers social trends that stretch farther into the future and undertakes research with the aim of achieving innovation in the future. In terms of our scope of research, we also intend to work on cross-disciplinary activities that are not covered by the individual technology platforms and research topics of the Center for Technology Innovation, as well as on new fields. Specifically, we have defined four areas of activity for our more than 100 researchers, namely physical sciences, life sciences, information sciences, and "frontier."

To get the maximum output from a small number of people, we have adopted "open innovation" as the basis of our approach to research, involving collaboration with universities, public research institutions, and other companies. We are also aware of the need to be able to determine how much value the outcomes of our research are providing to society, and have taken steps to ensure this. We aim to work with the government, local communities, and others to solve the challenges that society will face in the future, and to be an open research institution that articulates a distinctive vision and pioneers new fields.

Nagai: In a select group, individual researchers can play a major role. Do you take any special steps to improve motivation?

Yamada: Along with having a staff of people with very strong research capabilities and people who excel at coordination, the organization has a flat management structure in which project teams report directly to the center manager. Highly experienced chief scientists also provide inspiration. I believe this enables prompt decision-making and provides the flexibility for teams to join or work together and make the most of their respective capabilities.

Nagai: It seems to me that targeting future innovation demands a high-level perspective that involves the building of a vision.

Yamada: As the Center for Exploratory Research is not a particularly large organization, rather than setting out to plan the future by ourselves, we are building a distinctive vision through activities such as committee work and involvement in national projects based on an awareness of long-term national policy and societal challenges. Meanwhile, there is also value in challenges for the not-so-distant future that are in the process of happening now and have been raised by organizations such as the Global Center for Social Innovation and Center for Technology Innovation. In any case, a deep understanding and knowledge of science remains the essential basis for innovation. While there are the

Shinji Yamada, Ph.D.

General Manager, Center for Exploratory Research, Research & Development Group, Hitachi, Ltd.

Joined Hitachi, Ltd. in 1998. After holding positions that included head of the Materials Research Center at the Hitachi Research Laboratory and Electronics Research Center at the Central Research Laboratory, he was appointed to his current position in April 2015. Dr. Yamada is a member of the Chemical Society of Japan and the Society of Nano Science and Technology.

differences from past basic research that we talked about earlier, the emphasis on science is something we intend to maintain.

Nagai: While diversity is recognized as a strength in design thinking, one of my own areas of research, no doubt you also emphasize breadth in exploratory research. What form do you see this "breadth" taking in terms of the topics for research at the Center for Exploratory Research?

Yamada: While seeking to uncover the true nature of phenomena is essential to obtaining a deeper understanding of science, when the information and life sciences are brought into the mix, a need also arises to consider the true nature of people and society. With the human sciences increasing in importance, I have a sense that the scope of research is expanding. By selecting topics for study from this broader perspective, we aim to perform innovative research.

Toward R&D that Designs Innovations

Nagai: I get the impression that, by restructuring into three organizations, you have expanded the potential for R&D at Hitachi.

Yamaashi: That's right. With the Global Center for Social Innovation working alongside customers on the collaborative creation of solutions, the Center for Exploratory Research seeking out future value through open innovation, and the Center for Technology Innovation creating the necessary technologies, the R&D organization is able to work together or in complementary ways under these three distinct visions, giving us an ideal organizational structure for facilitating the global expansion of Hitachi's Social Innovation Business. In the future, we also aim to create a greater sense of unity by encouraging personnel exchanges between the organizations as part of specific projects or other activities.

Nagai: Hitachi is engaged in a transformation throughout its operations to better equip itself for future growth and innovation. How is R&D participating in this process?

Suzuki: My particular focus is to firmly establish global operations. As Hitachi's management shifts toward greater autonomy in regional decision-making, our first priority is to establish a framework for R&D and business divisions in each region to work together as one to deliver solutions. The Global Center for Social Innovation will further evolve to enable Hitachi to play a central role in taking on the challenges faced by specific regional communities and the global community.

Nishino: The focus for the Center for Technology Innovation is the development of "number one" technologies, products, and solutions. This use of the term "number one" is not boastfulness, rather it means we are seeking to deliver value in a form that customers genuinely want through the rigorous adoption of customer-oriented practices.

Yamaashi: To achieve this, in addition to keeping pace with rapidly changing technology trends, I believe we also need to be selective and focused in deciding which technologies we should enhance further, and where we should introduce technologies from other companies, while at the same time collaborating with the Global Center for Social Innovation and Center for Exploratory Research. From the perspective of social innovation, unifying and revising technology platforms from throughout Hitachi is also one of the major objectives of this current restructuring.

Yamada: As it works toward future innovation, I hope to see the Center for Exploratory Research become a source of pleasant surprises. A major aim of the center is for it to become a hub for exploratory research both in Japan and further afield. By working with key opinion leaders in a variety of fields and establishing research clusters, it will come to play a central role in the world of exploratory research.

Nagai: As I see it, this reorganization of R&D at Hitachi is a genuine example of innovation design. It is establishing an organizational structure based on a clear vision and in which everyone concerned can feel personally involved. While that is easy to say, there are few organizations that have actually achieved it.

At JAIST, we are going through a reorganization based on the two core concepts of service science and innovation design that is aimed at leading the process of identifying the needs of the future and delivering innovations from the Hokuriku region, which is a fertile soil for culture and technology. Today's discussion has left me with some valuable ideas for our own organizational reforms. The reforms at Hitachi look set to provide a successful example of innovation design that will change how R&D globalization is handled at Japanese companies and the very nature of R&D.

Overview

Hitachi's R&D Strategy

Tsukasa Ariyoshi

R&D AS A DRIVER OF THE SOCIAL INNOVATION BUSINESS

UNDER its Mid-term Management Plan that runs until FY2015, Hitachi has been strengthening its Social Innovation Business throughout the world. This business involves working with customers to achieve social innovation by jointly identifying challenges and then mobilizing the commercial resources of Hitachi, which include technologies, products, services, and expertise, to supply solutions to those challenges. Research and development (R&D) is one of the drivers of this business, and its role goes beyond just producing technology and other knowledge to also include enhancing capacity for innovation by utilizing these to find ways of creating new value that will provide business opportunities. To achieve this, Hitachi is pursuing the following three strategies.

The first is to expand collaborative creation with customers. The challenges being faced by customers and other parts of society are becoming more complex, encompassing problems such as energy and the environment, food and water, transportation systems, and security. Hitachi works alongside customers on these problems and is stepping up its activities aimed at the joint development of solutions. To achieve this, it is establishing a customer-oriented R&D organization that includes its recently expanded overseas R&D facilities. Measures also include accelerating business expansion by establishing common platforms for collaborative creation with customers.

The second strategy is the development of innovative technologies that meet market needs. With the aim of delivering innovative products and services that are competitive in global markets, Hitachi is strengthening the solid base of technologies it has built up across a wide range of businesses. As creating new solutions through the optimal combination of technologies is also important to progress on social innovation, this strategy includes the fusion of different technologies.

The final strategy is to work on challenges for the future. Hitachi believes that fundamental research based on a distinctive vision that the public and customers have yet to recognize is essential to its own sustainable growth and that of society and customers. This means undertaking R&D in new fields with a long-term perspective that anticipates upcoming social change. Also essential to realizing its vision is to forge a variety of partnerships and relationships. Hitachi intends to actively pursue open innovation both with customers and with countries, regions, and other technology partners.

The following sections provide an overview of the R&D organization at Hitachi and describe the actions being taken to implement this strategy and achieve future growth.

R&D ORGANIZATION AT HITACHI

The main business units within Hitachi at the current point in time include the Power & Infrastructure Systems Group, Information & Telecommunication Systems Group, Construction Machinery Group, High Functional Materials & Components Group, Automotive Systems Group, and Healthcare Group, which operate in the information & telecommunication systems, power systems, social infrastructure & industrial systems, electronic systems & equipment, construction machinery, high functional materials & components, automotive systems, smart life & ecofriendly systems, and financial services markets. For example, the Power & Infrastructure Systems Group deals with such markets (and associated customers) as electric power, manufacturing, public works, urban infrastructure, and transportation, while the Information & Telecommunication Systems Group mainly deals with finance, public works, industry, logistics, and telecommunications. Similarly, the Healthcare Group seeks to help the population live long and healthy lives by using information and medical technology to satisfy increasingly diverse needs throughout the care cycle that extends from prevention and examination to testing and diagnosis, treatment, and recuperation.

Hitachi's annual investment in R&D totals about 340 billion yen, the majority of which is targeted directly at R&D projects identified by the business groups as matching the requirements of their respective markets and customers in the short and medium term. In parallel, Hitachi also operates an R&D organization that is independent of these business groups.

Hitachi's very first research organization was the "research section" it established in 1918, just eight years after the company's formation. Since then, based on its Mission of "contributing to society through the development of superior, original technology and products," Hitachi has continued to set up new laboratories and restructure its organization in step with expansions and shifts in its business portfolio, including the establishment of the Hitachi Research Laboratory in 1934 and the Central Research Laboratory in 1942. By 2014, this had grown into an organizational structure that comprised four divisions in Japan (the Central Research Laboratory, Hitachi Research Laboratory, Yokohama Research Laboratory, and Design Division) and six overseas R&D centers (in the USA, Europe, China, Asia, India, and Brazil) under the name of the Research & Development Group.

The Research & Development Group has three core roles, described below.

Development of Technologies that Individual Business Groups Find Difficult to Tackle on Their Own

Because it specializes in R&D, the Research & Development Group can maintain the tangible and intangible resources that this work requires. Similarly, the many years it has spent working with a wide range of markets and technologies that cross the boundaries between different businesses have left the group with a collection of methodologies that represent research best practices, and platform technologies with broad applications. The group is also able to be selective and focused, assigning research resources flexibly based on the urgency and importance of the topic concerned. It is able to utilize these resources to tackle high-level problems based on the requirements of markets and the various business groups.

Development of Technologies that Span Multiple Business Groups

Because its business groups are organized along market lines, as described above, Hitachi needs to take care to avoid duplicating the development of common technologies. It is also not uncommon for a technology developed by one business group to be applicable to another, either as is or with only small modifications. Similarly, there is a need for R&D aimed at establishing business fundamentals such as reforming cost structures. Beyond considerations of commercial efficiency, there are also numerous instances of technologies that can be enhanced through the centralized development and accumulation of technologies from a variety of different market segments. In addition to serving as an important future resource for the R&D organization, this also provides the driving force behind the pioneering of new markets, as described below.

R&D Aimed at Entering Markets not Served by Existing Businesses or Creating Future Markets

Based on the following strategies, Hitachi is working on R&D that deals with this most crucial factor in the sustainable development of society, customers, and Hitachi.

(1) Keep up to date with information on markets to which Hitachi has access thanks to its involvement in a wide range of businesses.

(2) Keep up to date with the latest scientific developments by taking advantage of its involvement in R&D in the wide range of technical fields that underpin these businesses.

(3) Conduct research into methodologies, including those from the human and system sciences, for utilizing this information to identify signs of social change.

The factor that is crucial to all of these strategies is open innovation.

The Research & Development Group is formulating and implementing a long-term technology plan for these strategies under the direction of the Technology Strategy Office.

R&D Organization Facilitating Greater Innovation

As a further boost to social innovation, Hitachi has reorganized the Research & Development Group's three Japanese laboratories, Design Division, and its overseas R&D centers into the Global Center for Social Innovation, Center for Technology Innovation, and Center for Exploratory Research, to establish a customer-oriented R&D organization (see Fig. 1).

The Global Center for Social Innovation is a customer-facing organization that works with customers to develop solutions. It operates four

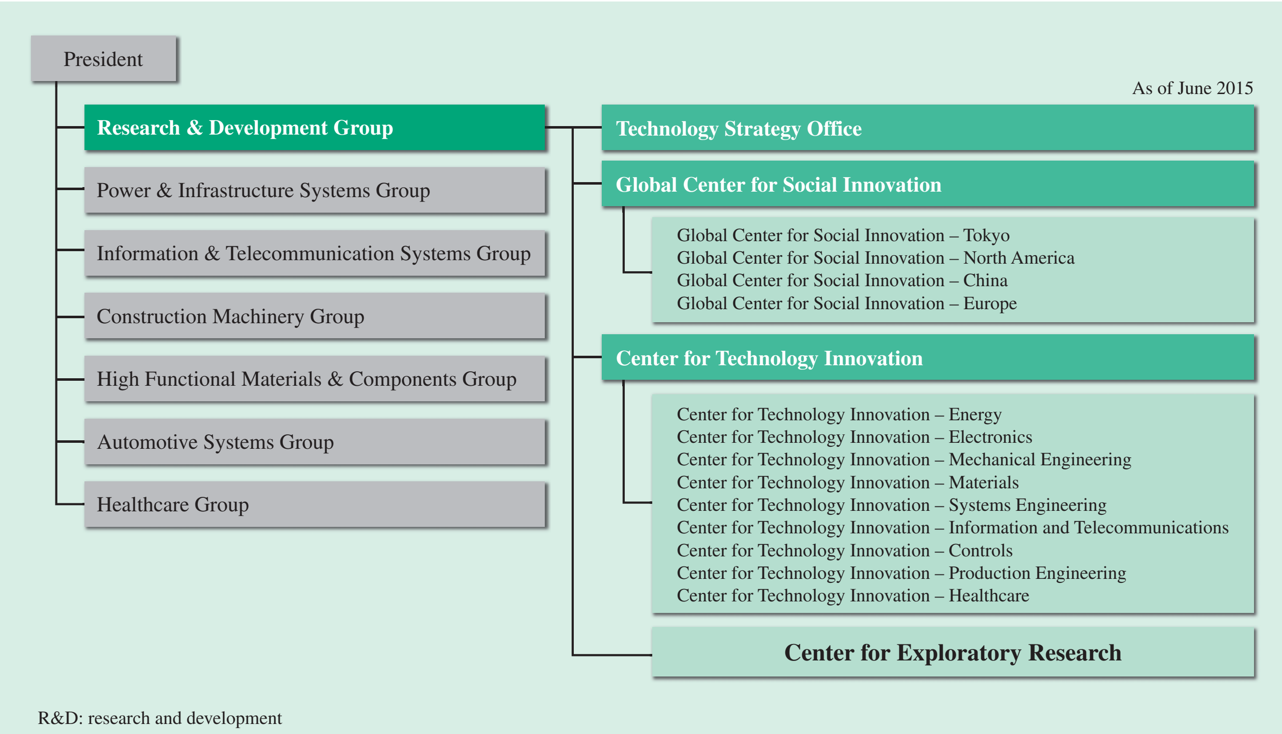

Fig. 1—Hitachi's Main Business Groups and R&D Organization.
The activities of the Research & Development Group include the development of common platform technologies and research into methodologies for creating new markets from a perspective that transcends the boundaries between business groups. In order to conduct customer-oriented R&D on a global basis, the group has also been restructured into three divisions ("centers").

centers, in Tokyo (Asia-Pacific region), North America, China, and Europe (see Fig. 2), that work closely with their respective regions on formulating and investigating ways of overcoming challenges, and that utilize the technology platforms and other innovative products of the Center for Technology

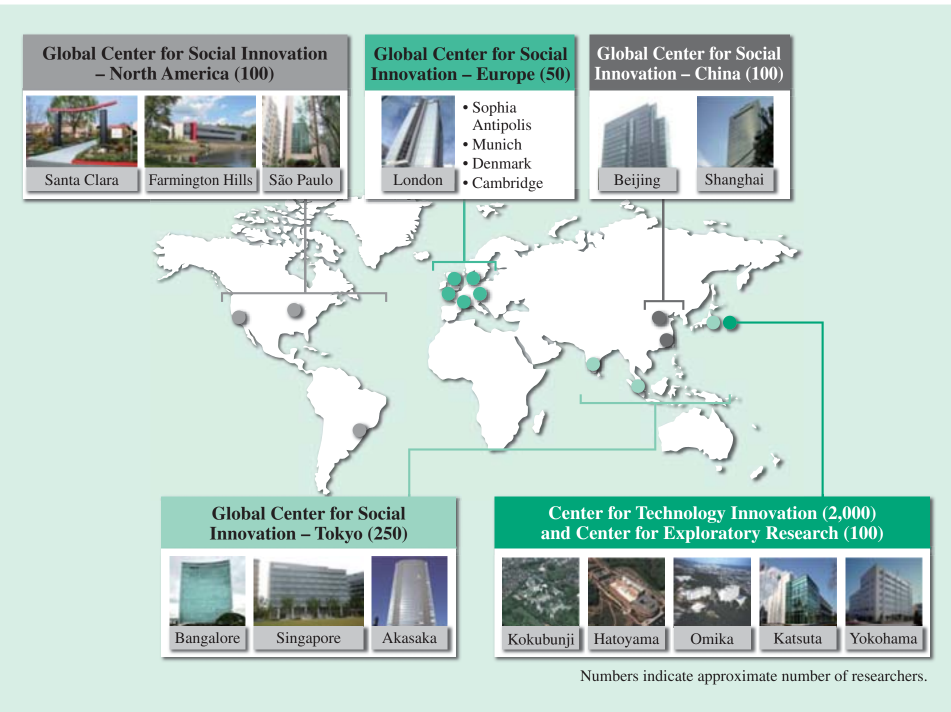

Fig. 2—Global R&D Facilities.
Hitachi is strengthening its Social Innovation Business around the world by establishing R&D facilities close to customers.

Innovation (described below) to provide leadership that extends from developing prototype solutions to conducting on-site testing.

The Center for Technology Innovation operates nine centers that deal with Energy, Electronics, Mechanical Engineering, Materials, Systems Engineering, Information and Telecommunications, Controls, Production Engineering, and Healthcare respectively. Its role is to support the development of new solutions through the optimal combination of a wide range of technical fields while also strengthening the technology platforms for these nine fields through the creation of innovative products.

The Center for Exploratory Research conducts leading-edge R&D from a long-term perspective on ways of resolving the challenges that society will face in the future, and also operates as a global open laboratory to open up new opportunities for Hitachi's Social Innovation Business through collaborations with a variety of other research institutions.

The following sections describe the R&D strategies of these organizations.

HITACHI'S R&D STRATEGIES

Customer-oriented Approach to Research

The Global Center for Social Innovation acts as a customer-facing organization so that R&D can drive the "customer-orientation" that is a key feature of the Social Innovation Business, establishing and enhancing collaborative creation processes that extend from sharing a common vision with customers to the formulation of new concepts, prototype development, and demonstrations and site testing.

To provide methods for working with customers to identify challenges and to formulate and investigate visions and solutions, Hitachi has already established NEXPERIENCE / Ethnography[a], the experience-oriented approach[b], and the NEXPERIENCE / Opportunity Finding[c] as proprietary service design techniques and set about expanding their scope of application[1]. NEXPERIENCE / Ethnography, for example, is a technique for identifying a customer's latent needs and underlying issues by having researchers observe work in progress. It has been used for applications such as coming up with ways of improving workplace productivity at a rolling stock maintenance depot in the UK, and in a variety of different workplaces, including data centers and the construction site for a proton beam therapy system in the USA, construction machinery maintenance in places like Australia and South Africa, and software development in China. In Kashiwanoha Smart City, it has been used to demonstrate the value of energy visualization and present specific usage scenarios from a user's perspective, facilitating the introduction of an area energy management system (AEMS) for optimizing the use of energy in the community. In addition to formalizing methods developed in the past, Hitachi is speeding up the collaborative creation process by implementing these methods in the form of information technology (IT) tools so they can be deployed as best practices throughout the world. In particular, NEXPERIENCE / Cyber-Proof of Concept (Cyber-PoC), a system that combines a variety of simulation tools to display in cyberspace the value provided by services and solutions, is helping build a common vision and sense of shared values.

NEXPERIENCE / Space that utilizes these tools are or will be operating in Tokyo (June 2015) and Santa Clara, USA (scheduled for November 2015).

Strengthening Technology Platforms to Assist Creation of Innovative Products

Hitachi is strengthening a wide range of technology platforms through the creation of the innovative products, software, and services needed for social innovation.

In the healthcare business, Hitachi is boosting development of particle beam cancer therapy systems and superconducting magnetic resonance imaging (MRI) systems that use strong magnetic fields. In the former case, work by Hitachi has included joint research with Graduate School of Medicine, Hokkaido University through the Japanese Cabinet Office's Funding Program for World-Leading Innovative R&D on Science and

(a) Ethnography
Originally used in fields such as anthropology and sociology, ethnography is a methodology for conducting field work to survey and record the behavior patterns of a society or other group. The term is also used for the survey documentation. It has been increasingly used by corporations in recent years to study consumers. Unlike statistical or quantitative analyses such as questionnaires, it is characterized by qualitative analysis using techniques such as interviews or observation.

(b) Experience-oriented approach
A new system development technique proprietary to Hitachi for working together with the customers who use IT to generate "experiences" (human experience values such as delight, impressions, or intellectual gratification) and share "impressions" during the progress of a project.

(c) NEXPERIENCE / Opportunity Finding
A method for identifying new businesses by predicting social trends based on future changes in the values held by consumers. It is used to envisage the future by conducting desktop research based around looking at printed or web-based material from the perspectives of a nation's politics, economics, society, and technology, and considering how these will interact as they change over time.

Technology (FIRST Program), and approval has been obtained for the manufacture and sale (as a medical device under the Pharmaceutical Affairs Act) of a new proton beam therapy system that combines realtime tumor-tracking[(d)] and spot scanning[(e)], two advanced radiotherapy techniques[(2)]. Elsewhere, the Research & Development Group has strengthened its capabilities in fields such as virtualization for high-capacity storage systems, which are used by the information and telecommunication systems business, and in large-scale analysis techniques for the development of crashworthy structures for high-speed rolling stock, which are used in the railway systems business. It has also developed an active vibration control system to be used in the world's fastest elevator (as of June 2015) for the infrastructure systems business, and a double-sided cooling technique for building smaller inverters for the automotive systems business.

It is also working on innovations that combine these technology platforms to provide new forms of added value. In a demonstration project being undertaken in partnership with the Bonneville Power Administration of the U.S. Department of Energy, Hitachi is developing a grid stabilization system for preventing major power outages by combining power system analysis techniques with IT.

R&D from a Long-term Perspective

The most important mission of R&D is to lead the way toward long-term growth. To achieve this, the Research & Development Group seeks to anticipate future challenges and engage in creative leading-edge research that can provide new forms of social innovation or other paradigm shifts. These activities are focused in particular on the physical, life, and information sciences. In the physical sciences, this includes advanced techniques for simulating physical phenomena and atomic-resolution electron microscopes for developing innovative materials, and theoretical developments aimed at creating these technologies. In the life sciences, research topics include regenerative medicine and single cell genome analysis. In information science, Hitachi is working on research into new computing concepts for the high-speed solution of combinatorial optimization problems, and on the analysis of things like brain activity and human behavior. In response to societal challenges such as population growth, and energy and food problems, work is also proceeding in new fields based on a vision of creating a sustainable society.

To develop innovations that can overcome the diverse challenges faced by customers and other parts of society, it is essential to work with customers and other technology partners, and with government agencies in Japan and elsewhere. Hitachi seeks to act as a hub for open innovation and to drive the development of future social innovations.

EXAMPLES OF INNOVATIVE R&D

This issue of *Hitachi Review* is dedicated to innovative R&D. It includes a total of 11 articles that present examples of this work, grouped under the categories of collaborative creation with customers, technology innovation, and exploratory research. The Category Overview provides summaries of each of these articles.

The first two articles present examples of collaborative creation in the form of an imaging solution and a solution for improving the efficiency of hospital management. The next seven articles deal with technology innovations, describing products for the home appliance, security, industrial, healthcare, and automotive equipment markets and the innovative technologies that make them possible. The final two articles look at exploratory research. These describe wearable sensors that can measure "organizational activity," a parameter that correlates with levels of happiness in an organization, and a new computing concept for the efficient solution of combinatorial optimization problems.

This issue also includes a "Special Article" on the atomic-resolution holography electron microscope that achieved world-record resolution.

TOWARD FUTURE GROWTH

Hitachi has a track record of creating solutions that provide more advanced social infrastructure for energy, water, resources, urban development, and logistics by combining the latest IT with the infrastructure businesses it has built up over many years. For the ongoing growth of its Social Innovation Business, Hitachi recognizes the importance of establishing common platforms that can provide

(d) Realtime tumor-tracking
A synchronized radiotherapy technique whereby metal markers are implanted near a tumor and two X-ray fluoroscopes used to detect their locations and calculate them in three dimensions so that a particle beam can be applied at those instants when the markers are within a few millimeters of the intended location.

(e) Spot scanning
A technique for pinpoint irradiation in which the particle beam is scanned over the target area and applied one spot at a time. This allows the particle beam to be targeted with high accuracy to match the complex shape of the tumor.

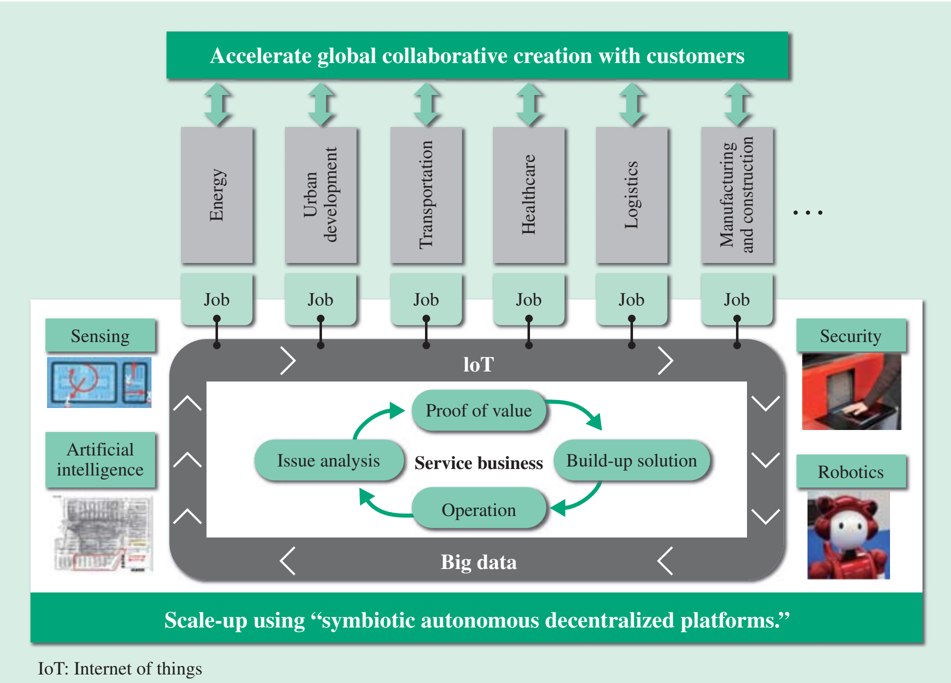

Fig. 3—Common Platforms for Expediting Social Innovation. Hitachi is accelerating the pace of collaborative creation with customers throughout the world using common "symbiotic autonomous decentralized platforms" that link value chains together across different industries and activities.

innovation as a service. New services will be provided by using the "symbiotic autonomous decentralized platform," a common platform based on the IoT[f], to analyze customer challenges, verify benefits, and build and operate solutions (see Fig. 3). The term "symbiotic autonomous decentralized system" refers to the system-of-systems concept whereby individual autonomous decentralized systems that have been optimized on a standalone basis are linked together via the IoT so that their collective operation can be optimized through "symbiosis" using artificial intelligence techniques. This enables solutions to be expanded from a scope that only encompasses a particular industry or activity into large systems that connect across different industries and all the way along the value chain. Artificial intelligence that can analyze indicators of system-wide efficiency will play an important role in achieving such "symbiotic autonomous decentralized" systems, as will sensing techniques for big data collection, security for information exchanged between systems, and techniques from robotics for interfacing with the real world. Hitachi intends to expand its Social Innovation Business and drive growth by working on the research and development of these technology platforms and by building platforms in collaboration with customers.

(f) IoT
Abbreviation of "Internet of things." By providing network connections for the exchange of information among a wide variety of devices that have not been connected in the past, the IoT enables things like automatic recognition or interdependent control.

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Category Overview

Sharing Challenges with Customers and Working together on Solutions
—Global Center for Social Innovation—

ROLE OF GLOBAL CENTER FOR SOCIAL INNOVATION

THE Global Center for Social Innovation forms a global research and development organization established for the purpose of working together to look at challenges from the customer's perspective and to supply solutions.

This article will begin by looking at the activities of the Global Center for Social Innovation. The first step in collaborative creation is to use proprietary service design methods and NEXPERIENCE / Ethnography to work with customers to identify the challenges they face, and then to proceed with steps such as formulating a vision or investigating ways of overcoming those challenges. The second step is to generate new concepts that can provide a high level of value to the customer and to implement them in the form of a prototype or demonstration. Based on the results of this work, the third step is the proof of concept at the customer site and to develop it into a solution. In addition, the intention is to deploy the same solution for other customers within the same industry and in different industries. Prototype development and proof of concept involves the supply of solutions that are proprietary to Hitachi, utilizing the portfolio of technologies built up through its past activities (see Fig. 1).

Because the markets that Hitachi is targeting with its Social Innovation Business extend throughout the world, the Global Center for Social Innovation has adopted a four-hub structure based on the objective of expanding collaborative creation by locating researchers close to customers. This is comprised of the Global Center for Social Innovation – Tokyo serving Japan and the Asia-Pacific (APAC) region, the Global Center for Social Innovation – North America serving the Americas, the Global Center for Social Innovation – China serving China, and the Global Center for Social Innovation – Europe serving Europe, the Middle East, and Africa (EMEA), with approximately 500 staff providing global coverage. As its name suggests, it is a global research organization that aims to contribute to the customer-oriented Social Innovation Business.

OPERATIONAL PLANS FOR EACH CENTER

While engaging in collaborative creation with customers

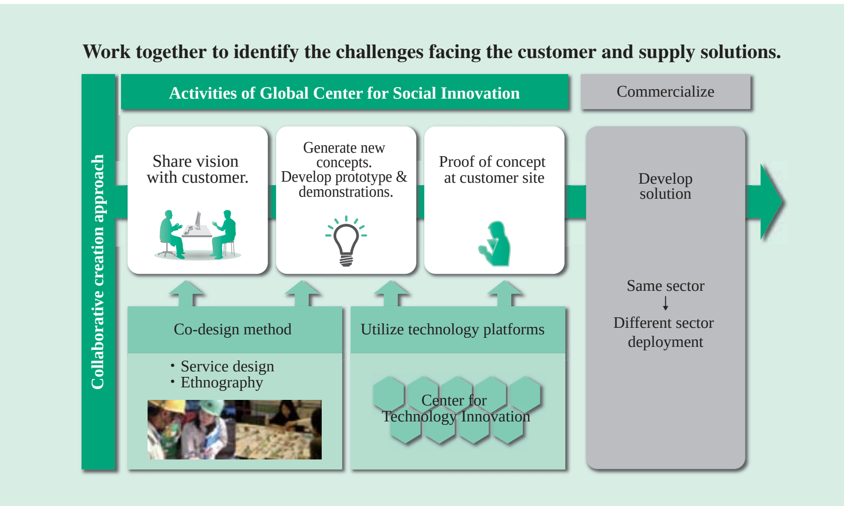

Fig. 1—Role of Global Center for Social Innovation.
The centers handle all collaborative creation processes from sharing vision with the customer to proof of concept at their site.

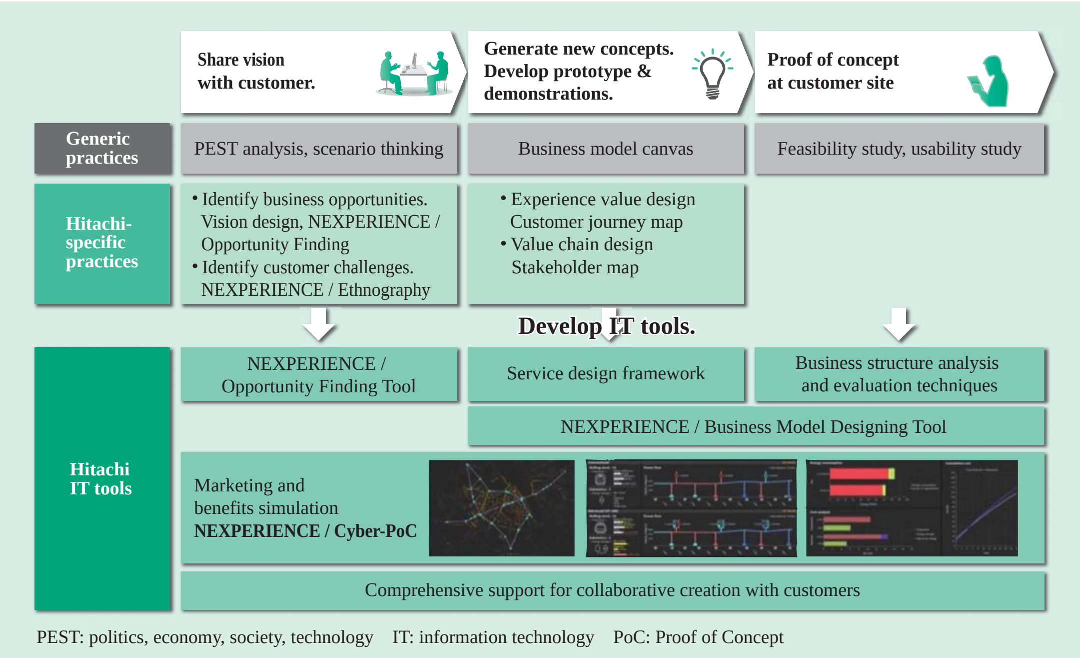

Fig. 2—IT-based Methods for Collaborative Creation with Customers under Development at Global Center for Social Innovation – Tokyo.
Hitachi aims to accelerate each phase of the customer collaborative creation process by implementing both generic and Hitachi-specific practices as IT systems.

to serve the global market, the centers will also align their operations with their respective region's business environment and strategies. The following sections describe the operational plans for each center.

Global Center for Social Innovation – Tokyo (APAC, including Singapore and India)

Based primarily in Tokyo, the Global Center for Social Innovation – Tokyo implements customer collaborative creation techniques developed through design and other service research in the form of tools that use information technology (IT), and utilizes them for the collaborative creation of solutions with key accounts in Japan and the Asian region.

The former Design Division and Yokohama Research Laboratory have already developed a variety of customer collaborative creation practices. Examples include the NEXPERIENCE / Opportunity Finding Tool, which collates societal issues and future changes in the perception of value, and the customer journey map, which provides a visual representation of users' ideal experiences[1]. The effectiveness of these methods has already been demonstrated through their use in numerous customer collaborative creation projects. Accordingly, the center is working to implement these practices as IT tools in order to provide a further boost to the pace of customer collaborative creation (see Fig. 2).

Also under development is NEXPERIENCE /Cyber-Proof of Concept (Cyber-PoC), a tool that combines a number of simulators to visualize business value. By using customer data as input, NEXPERIENCE / Cyber- PoC enables Hitachi to work with customers to verify the cost-benefit of social infrastructure projects prior to construction.

Hitachi launched a customer collaborative creation infrastructure that combines these tools in Akasaka, Tokyo in June 2015. The intention is to roll this out to the Global Center for Social Innovation – North America during FY2015 and to the Global Center for Social Innovation – China and Global Center for Social Innovation – Europe in FY2016.

The center also has operations in Singapore and India that will serve as bases for software development in addition to working on customer collaborative creation in Asian markets where ongoing development is anticipated.

Global Center for Social Innovation – North America (including Brazil)

The operations in North America will establish platforms for big data analytics and use them as a basis for developing applications in fields such as energy, telecommunications, finance, and healthcare. Making these analytics platforms available globally will enable application development to become more efficient.

Specifically, ongoing development is centered on the Big Data Laboratory that opened in June 2013, utilizing big data analytics to develop network analysis solutions for the telecommunications industry and production optimization solutions for the oil and gas industry(2). In Brazil, Hitachi is working with universities with the aim of creating solutions such as productivity improvements for agriculture and mining.

Global Center for Social Innovation – China

The center in China uses collaborative creation with customer to develop solutions based around a core of market-leading products, such as escalators, elevators, and automated teller machines (ATMs). They also collaborate with cities, other companies, and universities on measures for things like new forms of urban development and a low-carbon society.

To enable new forms of urban development, the center is working with the National Development and Reform Commission of the People's Republic of China to create urban and building solutions through collaborative creation with developers and city public institutions. In relation to policies for encouraging use of IT, the center is seeking to create financial solutions that use Hitachi's ATM business infrastructure through collaborative creation with local financial institutions(3), and healthcare solutions that draw on its know-how in hospital administration through collaborative creation with medical institutions.

Global Center for Social Innovation – Europe

In Europe, the center aims to solve challenges facing leading customers and regions and mature societies, and to deploy these solutions globally. Examples include the collaborative creation of solutions for preventive medicine and improvements in the efficiency of hospital administration in response to the shortage of caregivers, falling number of young people, and rapid rises in healthcare costs that accompany an aging population. It also includes the collaborative creation of solutions for smart energy and railway maintenance systems in response to the fall-off in efficiency resulting from aging infrastructure.

FUTURE DEVELOPMENTS

Through their customer collaborative creation activities, the Global Center for Social Innovation operates as a customer-focused and global research and development organization that works with customers to identify the challenges they face and to supply innovative solutions. Through its Social Innovation Business, which utilizes the Internet of things (IoT) and big data, Hitachi also intends to improve people's quality of life (QoL) and to help provide local communities with a bright future by helping overcome societal challenges that are becoming more complex throughout the world.

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Featured Articles

China Video Solutions: Promoting City Security, Service Quality and Values through Intelligent Visual-perceptions

Peng Yang
Tsutomu Imada
Kai Liu
Daisuke Matsubara

OVERVIEW: Rapid growth of high-quality video devices, video platforms and related services in the smart city environment of China offers huge application and business potential to intelligent video analytics and search. On the other hand, the special aspects of encoded video and visual space (e.g. volume, complexity, diversity) present many obstacles to fully exploring the information and insights in the video content. China Video Solutions, including its video search platform and related platforms, are created to overcome these obstacles with key technologies such as super-high speed video search, intelligent video analytics, strong front-end embedded video platform, light-weight video processing and a flexible video platform. With intensive customer-oriented technical/business practices in China, it shows great potential for making good contributions to the super-secure metropolitan, high-quality city services and value-added applications.

INTRODUCTION

WITH the rapid development of the whole of Chinese society, video-related devices and systems, which can generate multimedia content (especially video content), have increased dramatically. And, the quality of video content generated has been enhanced, which has driven a great increase in the average bit rate and data volume of video content. In the meantime, the informational entropy contained in video content is much higher than other data forms (e.g. text, log). So, more and more services and applications have been built based on video equipment and platforms.

Based on the predictions of CCW in 2015[1], this category could support business of over trillion USD in the next five years. As shown in Table 1, the city infrastructure with video-related entities has made great progress. Although huge market and service potential have been witnessed in related fields, this trend imposes great pressure on the capability of cyber systems and technologies. First of all, the resources for encoding, decoding, storing, analyzing, searching and managing of video content must be greatly increased. In order to fully explore the insights within the video content, video/image information analysis and retrieval are required to describe, store, and organize multimedia information. So that, advanced algorithms and platforms are mandated to assist people in detecting realtime events and finding video objects/resources conveniently and quickly.

China Video Solutions are designed and developed to overcome the technical obstacles of applying visual intelligence in a smart city environment. They are composed of a video analytics/search platform, a Chinese product, a strong embedded intelligent video platform, and a large-scale video platform. Many advanced technologies such as intelligent video search, analytics, management and optimization have

TABLE 1. Migration of Video-related City Infrastructure
City infrastructure with video-related entities is making great progress in China.

Aspect	Previous status	Current status
APP fields	Only safety	Safety, transport, social services, enterprise, etc.
Coverage	Limited area with limited cameras	Whole city with huge number of cameras
Quality	CIF/4CIF	720P/1,080P, 4K soon.
Data volume	2 to 5 Gbyte/ camera per day	20 to 50 Gbyte/camera/day, 35 million hours of video content in mid-city
Network	Narrow band	Wire/Wireless broadband
Intelligence	N/A	Wide-spread intelligence
Platforms	Single/Isolated	Integrated/Cloud

APP: application CIF: common intermediate format been applied to improve the level of safety, quality of services, and value-added applications in the smart city domain.

CURRENT PROGRESS AND PROBLEM STATUSES

Current Status

As indicated in Fig. 1, in the Chinese metropolitan environment, the most rapid development of intelligent video applications and services has been seen mainly in three categories.

Obviously, the fastest growing segment is the industry of public safety, more specifically, intelligent video surveillance. With the threat of terrorism, federal, state and local governments are devoting greater resources to video surveillance. Enterprise and related non-profit entities face the same issues as governments, such as industrial espionage, sabotage or theft. To prevent loss, retail businesses invest in storewide security cameras. Governments and corporations find video surveillance is a vital segment of their security solutions. In this category, entities with large-scale systems, such as the city department of public safety, are more likely to use the full capabilities of video analytics and video search. Meanwhile, other information from the security domain is integrated with the results of video intelligence to enhance the capabilities of security.

Another important category is utilizing video intelligence to enhance the service quality of city life. A huge amount of investment has been witnessed in transport, banks, environment protection, and other sectors. Run-time status in the city environment is more and more important in order to calibrate the resources of public services. Video analytics and search are obviously the most suitable ways to fulfill those requirements. The diversity of features, such as face, car, complicated behavior, and environmental change, based on video analytics is a notable phenomenon.

Besides the non-profit categories in the city environment, intelligent video applications also show very good potential in profitable fields. Business owners in multiple fields (e.g. commerce, residence, media, transport) utilize results from video intelligence to create new applications and to improve the performance of current ones so that they can directly sell new services or indirectly boost services that are already profitable. As above, a diversity of features is also in demand by customers, and intelligent video

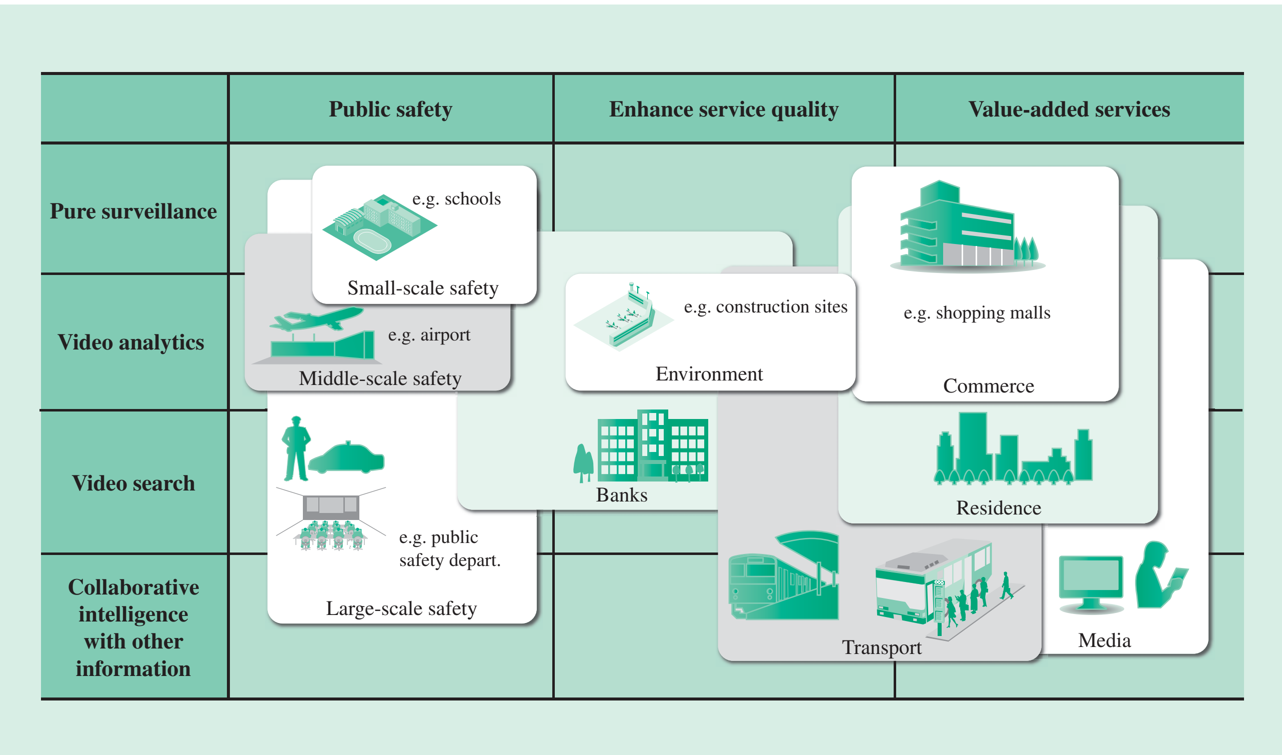

Fig. 1—Correspondence between Application Domains and Technical Categories.
Different fields in a smart city have different preferences for service requirements and technical requirements. Huge diversity has been observed regarding intelligent video technologies.

functions are always integrated with Internet/mobile Internet technologies to increase the usability and penetration for public citizens.

Intelligent video technologies have the virtues of easy installation, low maintenance, and one-stop entry for rich information and features. So, the broad applicability and strong support capability for services are making the number of video applications grow very fast.

On the other hand, in order to fully utilize the potential of intelligent video technologies, there are also many challenges in terms of technical aspects.

Technical Challenges

(1) Efficiency issues when searching a large volume of video content

Since the related architecture has been enhanced so much, the amount of video content generated has increased dramatically. In this sense, how to find a target object or specific video clips in a huge volume of content is a big issue. For instance, in a large-scale video surveillance system, such as on a city scale, searching for a human face could take more than 1,200 man/months. It is a huge burden for system operators and end users, and pretty much diminishes the usability and service quality. Some users created a system to add multiple tags in order to describe the video content with text. This way is okay for small-scale systems. However, in large-scale systems, creating the tags themselves will consume a huge amount of resources. And, a large portion of the video content is really difficult to describe. Lastly, tags for the same content could be different from person to person. So, differences in human understanding also devastate the usability of text-based video search.

In this sense, high speed and accurate content-based video retrieval are mandatory.

(2) Challenges for IT resources

One of the major technical challenges to deploying large-scale intelligent video applications is the high consumption of information technology (IT) resources, including computational resources [such as central processing unit (CPU)], storage resources (e.g. memory, disks), and networking resources. For example, one way of high-definition (HD) video stream can consume 6 Mbit/s for transmission over the network, one enterprise-class CPU core, and 512 Mbyte of memory for video decoding, one to two CPU cores, and 1 Gbyte of memory for video analytics with one feature, 50-Gbyte hard-disk for one day of storage, and related backup resources to provide reliable service. In large-scale systems, where hundreds of thousands of video cameras could be available in one city, the related costs as mentioned above will be a huge burden.

In the meantime, there are a number of circumstances where high-performance IT equipment cannot be deployed. Sites with high dynamics, such as running vehicles from public transportation or construction areas, have no conditions for providing good space, enough power, and the necessary cooling to support servers and storage. But, customers with such kinds of facilities still want to use video intelligence.

In this sense, the video systems and applications should not only be optimized to save resources, but also be customized to survive all kinds of local environments.

(3) Diverse requirements on multiple aspects

Video content potentially stores extremely rich content compared with text and voice. Mankind can explore much richer information from coded video. In different industries, the events or objects sought in video content could be quite different.

The visual perception of space in human beings shows great diversity, which is much more than what we can describe and depict. The same principle applies in the field of intelligent video as well. Based on a full market investigation of the necessary features in customers' minds, the result spans quite a board feature space, such as the bio-features of human beings, the behaviors of a single person or group of persons, vehicle features, city environment features, and the combination of or transition between the features mentioned above. Development of all these features by a single company could be a huge liability in terms of cost and time.

Meanwhile, all kinds of video systems have been deployed in the city environment for a long time. Most of them have no intelligent genes. While the new intelligent video functions are deployed, the integration with legacy systems could be quite challenging. Interfaces with all kinds of front-end devices, existing video management systems, a large number of applications/service systems from multiple customers, existing IT facilities, and management platforms must be considered.

As a short summary, although intelligent video technologies have brought great potential to high security, high quality, and high value in a smart city. Many technical challenges have been noticed as well. China Video Solutions are designed and developed accordingly to promote city security, service quality, and value through intelligent visual-perceptions.

CHINA VIDEO SOLUTIONS

The overall architecture of a China Video Solutions is mainly composed of video search platform functions and strong embedded front-end platform with light-weight analytics (see Fig. 2).

Inside the video search platform domain:

(1) Data Ingest Engine is mainly in charge of extracting, transforming, and loading (ETL) of video content from all kinds of devices and systems at static sites in the city environment.

(2) The Video Analytics Engine is the major component for doing all kinds of video analytics. It fetches the buffered key-images from the Data Ingest Engine. Intelligent analytics can be done based on JPEG frames, and feature vectors are extracted as results. Intelligent analytics functions should be defined and supported based on the application scenario. For example, in the category of public security, human faces, cars, or car license plates could be required to be detected.

All these features, created by analytics modules and related mathematical models, will be described by feature vectors, and registered in the feature database of the Video Search Engine, the main component for searching.

(3) The IT resource management engine is the central controller for all IT resources for static sites. The application (APP) engine is the portal for external applications and services.

In the meantime, the embedded front-end platform is created to do all kinds of video analytics at dynamic sites. In order to combat the technical challenges mentioned in "Technical Challenges," many key technologies have been developed.

Enhanced Content-based Video Search

An initial large-scale video search system has been developed by Hitachi's Center for Technology Innovation.[2] Its strength is in performing high speed video searches in large-scale systems. With regular personal computer (PC) servers, a single content-based search of 100 million key images could be

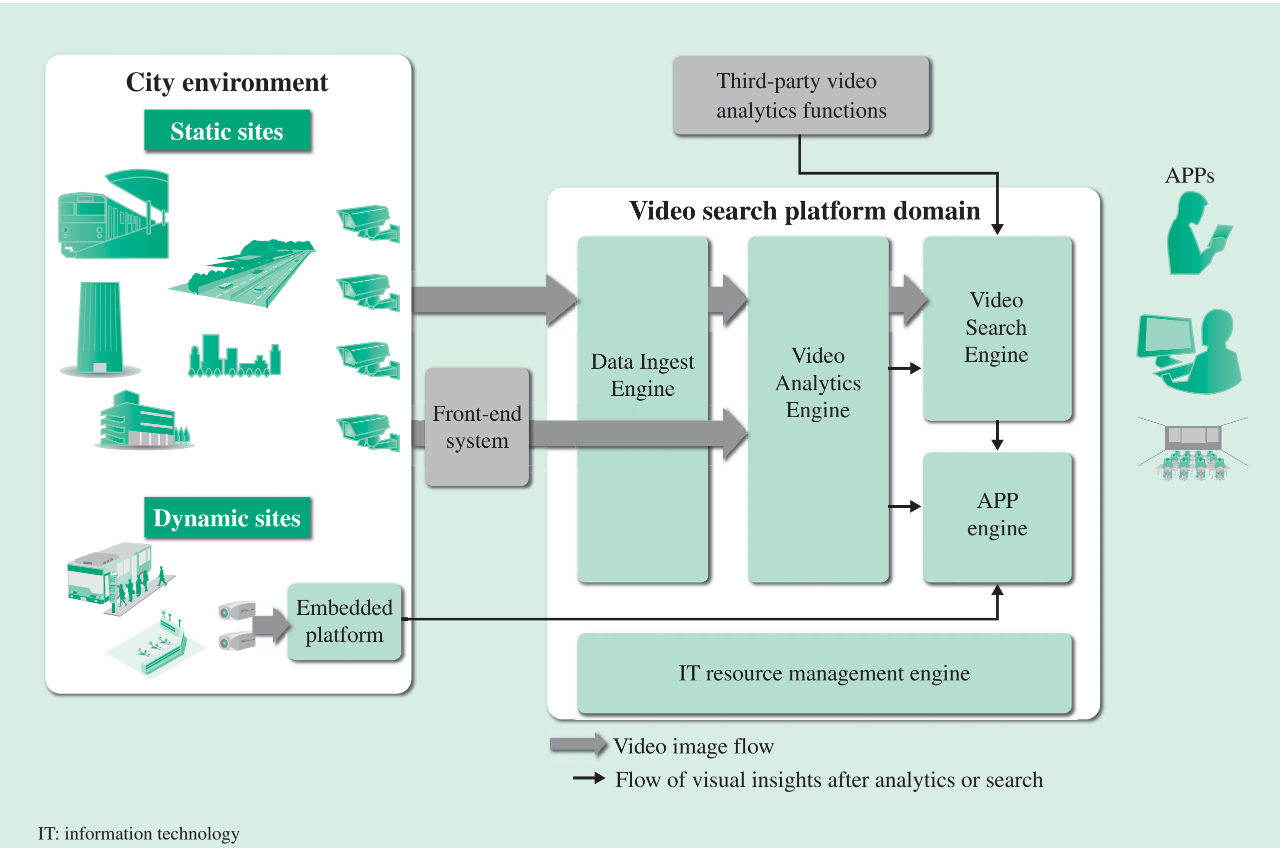

Fig. 2—Overview of the Solution Architecture.
Static sites are locations with video cameras in a static spot, reliable wired networks, and a server-friendly environment. Dynamic sites could be vehicles or construction sites, which could be moving, wireless networks, and a harsh environment.

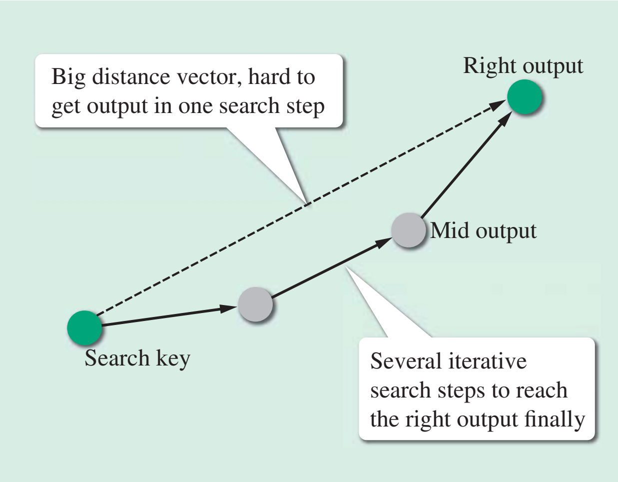

Fig. 3— Principles of Iterative Search.
In large-scale video search systems, a huge number of feature vectors, which are created as the result of video analytics, bring in huge noise. Iterative search is used to bypass the impact of the noise, and get the correct results in a limited number of steps.

finished within one second. The results of onsite trials show the efficiency of quick video search could be enhanced by more than 99%, when users try to find objects with key images in a large video database.

In China, the following new technical features have been developed to deal with super-large-scale video surveillance environments:

(1) Iterative search

In super-large-scale video systems, quite a few factors can contribute a lot of noise to video analytics. So that, the search accuracy over a huge amount of feature vectors will degenerate. Iterative search is developed to maintain the same search accuracy by taking several exploratory steps, as indicated in Fig 3.

(2) Scene-based filtering function

In search results, the same objects in continuous frames of the same scene are more likely to be shown together. It will decrease the valuable information when users want to show objects in multiple scenes. Therefore, a filter function has been developed in the APP engine to extract a single instance in one scene, while filtering out duplicate instances.

(3) Dynamic resource scheduling in the cloud

Because the scale of the video system is going to be big, private clouds are chosen by customers as the IT infrastructure. As shown in "Technical Challenges," intelligent video technologies could consume a huge amount of IT resources. So that, the scheduling of resources based on virtual machine management is necessary. In trials, with advanced algorithms for IT scheduling, 20% of resources could be saved.

Strong Embedded Platform and Light-weight Video Analytics

As indicated in "Current Progress and Problem Statuses" chapter, there are a number of dynamic sites where traditional analytics equipment (e.g. servers) cannot be deployed.

China's first all-in-one equipment has been developed to deal with this issue. It is an open platform based on embedded Linux[*1] with enough computational resources [CPU+digital signal processor (DSP)], video recording, and rich networks (WiFi,[*2] 2G, 3G). And, it is strong enough for harsh environments.

Meanwhile, to save cost, one device supports multiple analytics functions for multiple video channels. So, light-weight analytics algorithms, which traditionally cost a huge amount of IT resources, have been developed for this purpose.

The platform is designed to be open to any new light-weight algorithms in order to quickly and significantly accelerate the procedure for going to market.

Rich Interfaces

Rich interfaces have been developed to handle the obstacles of diversities as mentioned in "Current Progress and Problem Statuses" chapter.

(1) Interfaces to front-end devices/systems

In the Data Digest Engine, it supports interfacing with cameras from hundreds of camera vendors in China. And, it also can upload offline content from various storages.

(2) Interfaces to third-party video analytics

In fact, due to the quick industrial growth, many companies are working on algorithms for video analytics. This interface allows the Video Search Engine to register the result of external intelligent functions. Then, it can fully utilize functions from the entire industry.

(3) Web API for diverse applications

All kinds of application platforms can utilize the capabilities of this solution in a short time using this interface.

APPLICATION CASES IN CHINA

Large-scale Video Search for Public Safety

With the large scale involved in public safety, how to find a target person or car in a huge video database

*1 Linux is a registered trademark of Linus Torvalds.
*2 Wi-Fi is a registered trademarks of Wi-Fi Alliance.

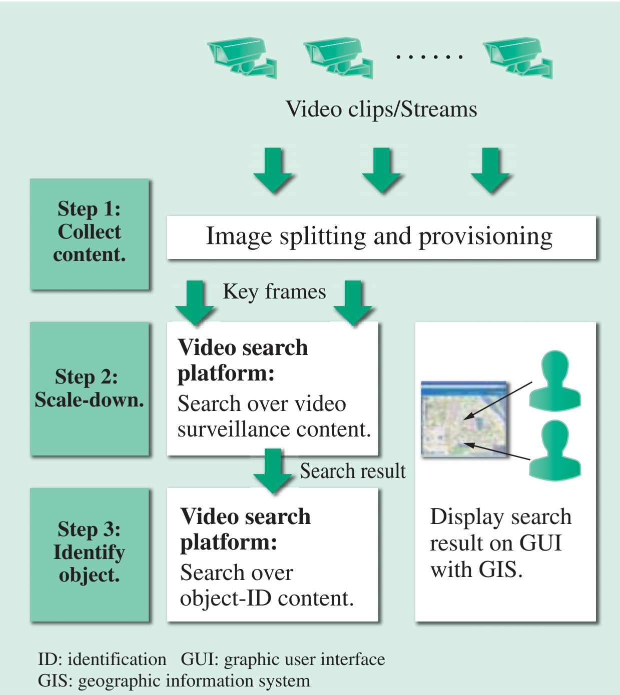

Fig. 4—Typical Work Flow in Video Search for Public Safety.
The video/image search is used to help the users filter the target objects (e.g. people, cars) quickly and accurately from a huge amount of video content.

must be a big issue. A typical service flow can be seen in Fig. 4. Basically, the search functions are utilized in order to narrow down the scope of the search and to find the target objects quickly and accurately.

In face search and car search trials in two cities in China (Table 2), this solution can achieve a quick search with 90%+ accuracy. Search speed has been increased by more than 99% in real practice.

Intelligent Vehicle Platform to Improve Service Quality and Add Value for Public Transportation

Although scheduling of public transportation has been practiced for many years, the usability of transport resources in a smart city is still not optimized. The major issue is that the current scheduling mechanisms are mainly based on information outside of vehicles, without considering the in-vehicle status of passengers.

Passenger density and number detection through video analytics based on the embedded platform have been achieved and operated in several cities in China. In accord with the diverse statuses of passengers in different buses/subways, public transportation resources (such as buses, vehicles, subways, trunks) could be further optimized.

TABLE 2. Onsite Results of Video Search for Public Safety
Video search can achieve quick search results with 90%+ accuracy, and its search speed has been increased by more than 99% in real practice.

Camera	City 1	City 2
1920×1080	100% (1 to 2 iterations)	N/A
1280×720	100% (1 to 2 iterations)	N/A
720×576	92% (2 to 3 iterations)	90% (1 to 3 iterations)

FUTURE DIRECTIONS

Although China Video Solutions have been recognized as having good potential in the Chinese market, there are still a number of fields that need to be further explored. Basically, this solution could be further expanded to more vertical fields in the smart city environment. In order to achieve this target, more analytics features should be developed or integrated in the near future. In the meantime, the strong intelligent embedded platform can be used in many other fields with dynamic environments. So that, more light-weight video analytics functions should be migrated to this platform.

Lastly, over-consumption of IT resources is still one of the major bottlenecks of intelligent video applications in China. Further optimization in algorithms, platforms, and management could be the focus of future effort.

CONCLUSIONS

Targeting the trillion-dollar market of China related to intelligent video technologies, China Video Solutions were created to further enhance the security, quality of service, and value of application in a smart city environment. With the world's leading capabilities in video search and video analytics, hybrid video platforms, rich interfaces and high-profile optimization capabilities, these solutions show good potential to further explore the usability of visual perceptions of mankind.

Friendly partnerships in a technical portfolio will provide good contributions to the entire industry in the next step. Based on these solutions, it is believed that more promising applications and services can be created in Chinese metropolitan areas.

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Featured Articles

Solution for Improving Hospital Management in Denmark

Shigeyuki Tani, Ph.D.
Iris Fermin, Ph.D.
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OVERVIEW: Denmark is a world leader in addressing the challenges that face mature societies. Both citizens and the government are working together to bring about social innovation through the early adoption and evaluation of innovative technologies. Hitachi established its Denmark Big Data Laboratory in Copenhagen in November 2014. The laboratory is engaged in the development of new service concepts through participation in joint trials with local institutions. Hitachi is participating in the "super hospital" concept consolidating public hospitals into 16 while also improving the efficiency of hospital management by 25%. To boost efficiency at hospitals that are increasing in scale or experiencing incremental growth, Hitachi is implementing hospital management solutions that utilize autonomous decentralized control technology and techniques for managing the flow of people and devices.

INTRODUCTION

THROUGH the Horizon 2020 program, European nations have identified seven challenges that face mature societies, including welfare, food, and transportation, and are working on ways of overcoming them. Based on a background that includes an integral role for information technology (IT) through the widespread adoption of electronic government, the Kingdom of Denmark in particular has set itself high targets in such areas as reducing the load on the environment and cutting healthcare costs, and is proceeding with the implementation of sophisticated policies aimed at overcoming the challenges it faces. Hitachi has established its Denmark Big Data Laboratory and has embarked on work aimed at implementing solutions to the challenges that face mature societies through "collaborative creation" projects with partners in Denmark.

INNOVATIONS FROM DENMARK

Although many people will likely think of Northern Europe as home to strong welfare states, this is predicated on citizens playing a central role in supporting society and represents a model for a new type of society to which mature societies such as Japan should aspire. However, there is no doubt that the welfare state comes with high costs. In response, Denmark has set out to use innovation to overcome this problem. As a result, the country has succeeded in using innovation to expand employment by 150,000 to 250,000 jobs each year in a total population of 5.6 million.

Features of Denmark

Two key features of Denmark are its international competitiveness and its ability to innovate. Ranked sixth in the world by per capita gross domestic product (GDP) in 2014, Denmark has remained ahead of Japan throughout the last decade[1] (see Fig. 1).

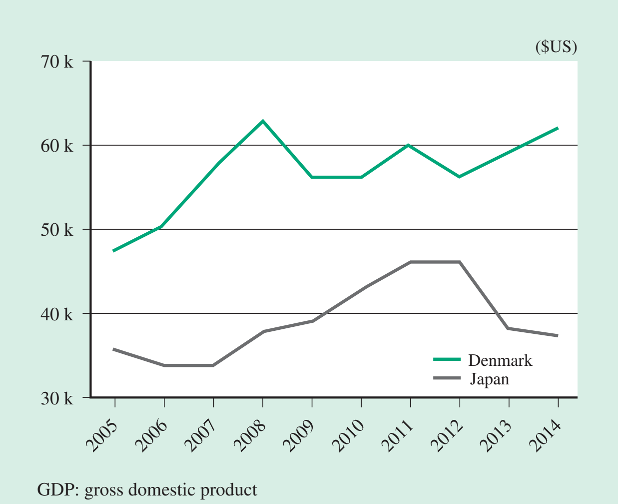

Fig. 1—Comparison of per Capita GDPs of Japan and Denmark. The figures are based on 2005 to 2014 data from the International Monetary Fund. Denmark's per capita GDP was higher than that of Japan throughout this 10-year period.

It ranked ninth in the 2014 world competitiveness rankings of the Swiss-based International Institute for Management Development (IMD), sharing its high ranking with other Northern Europe nations(2).

Having been an early adopter of innovative technologies and practices for addressing the problems faced by society, Denmark is pushing ahead with societal-level innovations. Despite being an oil producer, thanks to its North Sea oil fields, Denmark has actively pursued renewable energy and leads the world in per capita wind power generation capacity. Utilizing wind and biomass power, it already supplies one-third of its electric power needs through renewables, and has set a national target of increasing this to one-half by 2020, and of reducing fossil fuel use to zero to become carbon neutral by 2025(3).

User-driven Innovation

One feature of innovation in Denmark is that it is user-driven, with the tradition at Denmark's companies of proactively involving users in the development process having prepared the ground for this approach(4). This makes the country one that is quick to adapt to new technologies and other changes, with no hesitancy among citizens about participating in social innovation or trying out new technologies for themselves. With a test bed that provides opportunities for trial and error being essential to the development of innovative solutions, Denmark provides just the sort of environment needed for this.

The CPH 2025 Climate Plan is a plan published by the city of Copenhagen, the capital of Denmark, for taking on environmental challenges in the period up to 2025(5) (see Fig. 2). Among its objectives, Copenhagen is aiming to increase the proportion of citizens commuting by bicycle, with active involvement by citizens having already seen this figure rise to 35%.

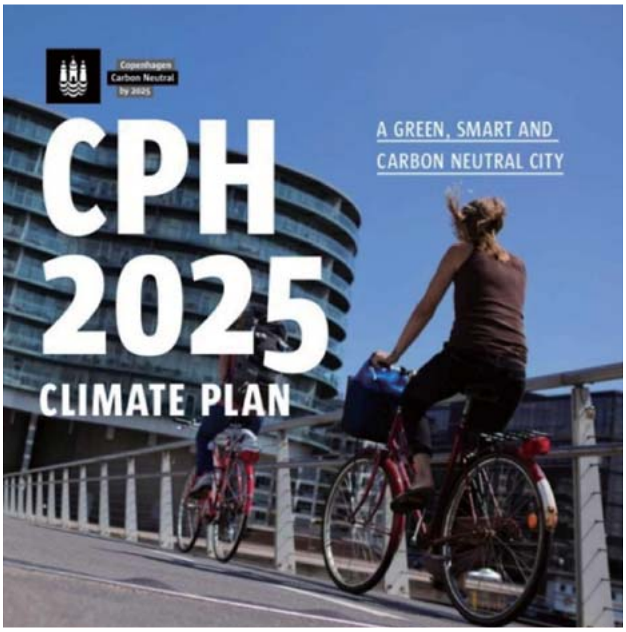

Fig. 2—CPH 2025.
The CPH 2025 Climate Plan published by the city of Copenhagen, the capital of Denmark, runs until 2025 and is aimed at reducing the load on the environment.

Utilizing Collaborative Creation with Customers for Solution Development

Hitachi established its Denmark Big Data Laboratory in Copenhagen in November 2014. Through involvement in industry-government-academia initiatives in Denmark's major cities and in collaborative trials featuring user participation, the laboratory is working on the development of new service concepts and the formulation of business models. Its work covers the fields of energy and the environment, transportation, and healthcare, each of which has been identified as a key area by the government of Denmark. In addition to contributing to national development through the collaborative creation of solutions with customers and other partners who are grappling with these future challenges in Denmark, the plan is also to deploy the solutions in other countries and areas that face the same issues.

SUPER HOSPITAL

Super Hospital Concept

In the healthcare field, Denmark is working on a "super hospital" concept. Against a background of rising social security costs due to increases in the cost of healthcare, the concept involves investing a total of 40 billion kroner over 10 years with the aim of consolidating 40 existing public hospitals into 16 "super hospitals" (advanced medical facilities) (see Fig. 3) while also improving the efficiency of hospital management by 25%. A distinctive feature of the plan is the choice of three particular indicators to help achieve these goals(6) (see Fig. 4).

Because of Denmark's implicit adoption of a quality-first philosophy, as exemplified by its user-driven innovation, it is looking to technologies that can provide highly efficient healthcare services without compromising the quality of medical care. In the city of Aarhus, construction of a planned huge super hospital is already underway on an expansive 4 km × 4 km site. Furthermore, because each region will

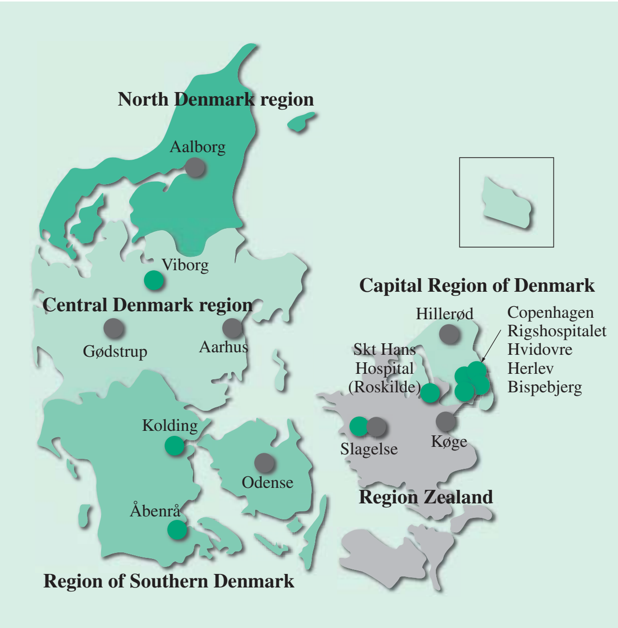

Fig. 3—Super Hospitals in Denmark's Five Regions.
Denmark will consolidate 40 existing public hospitals into 16 super hospitals. The grey dots indicate new construction and the green dots indicate expansion or refurbishment.

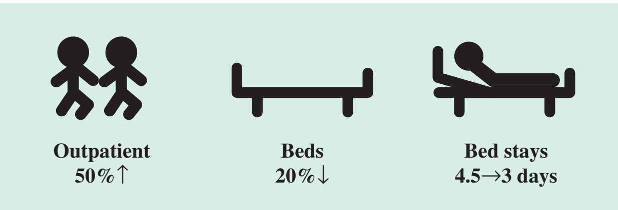

Fig. 4—Three Target Indicators of Super Hospital Concept.
Denmark has defined three targets for achieving a 25% improvement in operational efficiency: a 50% increase in outpatients, a 20% reduction in beds, and a reduction from 4.5 to 3 days in the mean length of a hospital stay.

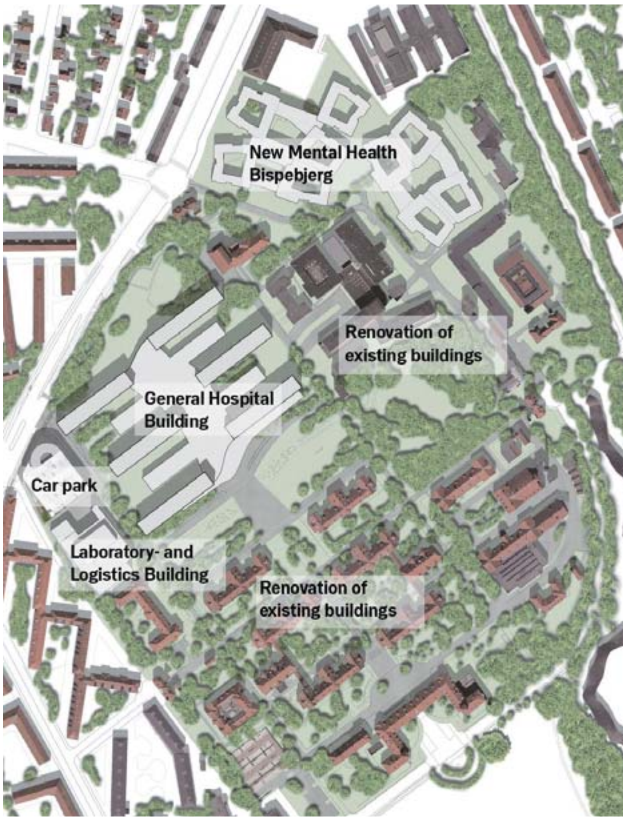

Fig. 5—Future Plan for Bispebjerg and Frederiksberg University Hospital.
The plan includes the construction of a new hospital on the north side of the site and, along with the merger of Bispebjerg Hospital and Frederiksberg Hospital, the new facility is to function as a super hospital.

be served by only three or four hospitals (see Fig. 3), meaning each super hospital will need to cover a wide range of services, information communication technologies (ICT) are anticipated to play a major role in supporting community healthcare.

Collaboration with Bispebjerg and Frederiksberg University Hospital

To participate in the super hospital concept and develop new healthcare solutions, Hitachi reached an agreement with the Bispebjerg and Frederiksberg University Hospital in November 2014 to work jointly on solution development(7). This joint development will combine the extensive medical and other data resources held by the hospital and its experience in hospital operation and management with Hitachi's experience and know-how in the supply of medical devices and systems and in the use of ICT for big data.

The Bispebjerg and Frederiksberg University Hospital was formed from a merger of Bispebjerg Hospital and Frederiksberg Hospital. It provides medical services to approximately 450,000 citizens in the Frederiksberg and Copenhagen municipalities. It has a staff of approximately 5,000, with major expansions(8) planned that will turn it into a super hospital covering 200,000 m^2 by 2025. Design and construction of a new hospital building commenced in 2014 (see Fig. 5). The work includes active measures aimed at making operational improvements through the use of ICT, such as sensors installed in temperature-controlled facilities at roughly 800 locations, including freezers and medical cabinets, for example.

Another objective is to look at the movement of people at the site to achieve an efficient flow of people and devices through the enlarged facility that will result from the super hospital concept.

USE OF COLLABORATIVE CREATION WITH HOSPITAL TO IDENTIFY CHALLENGES

Big Data Analytics

A feature of big data analytics that has come about through advances in computer technology is the ability to measure and assess specific circumstances to identify and classify particular features within the wider context, and to use these features as a basis for performing control in accordance with these specific circumstances. This does not mean control functions are restricted to the particular device on which they are running, as with past systems, nor does it mean only attempting to control overall trends, as in mass-marketing. Instead, less wasteful control is achieved by considering both specific circumstances and overall trends.

As noted above, Bispebjerg and Frederiksberg University Hospital has installed monitoring sensors in temperature-controlled facilities such as freezers and medical cabinets at roughly 800 locations. Hitachi conducted an analysis of roughly one year of temperature data from these sensors that identified and classified a number of features from within the wider situation (see Fig. 6). Based on these features and the specific circumstances at each of the locations, Hitachi found potential savings of more than 5% in the hospital's total cooling cost that could be achieved by performing control in ways that minimize waste. In the future, Hitachi will work with the hospital to investigate what forms of dynamic control to perform for the existing monitoring systems and the various temperature-controlled facilities spread across the site.

Ethnographic Analysis

Ethnographic analysis is a technique for identifying the structures and processes at a workplace through close observation of actual behavior at the site. By identifying patterns associated with workplace problems and enabling them to be understood at a conceptual level, this uncovers the underlying issues that will improve the "experience" of the solution being developed. Furthermore, because it uses observational methods, it can help discover latent needs by identifying tacitly assumed attitudes(9). An ethnographic analysis of doctors, nurses, pharmacists, and other hospital staff is already underway in collaboration with Bispebjerg and Frederiksberg University Hospital (see Fig. 7).

The greatest benefit of ethnographic analysis is its identification of issues that are not apparent from the measurement data alone. In the case of the temperature data described above, the measurement data may be adequate on its own if the only objective is to detect faults in the temperature-controlled facilities. If an ethnographic analysis of the workplace is conducted, on the other hand, it will identify that the important issue for the organization and staff is to manage the quality of medicine or food stored in these facilities. This then becomes a question of hospital logistics concerning how, when, and where this medicine and food are distributed (allocation).

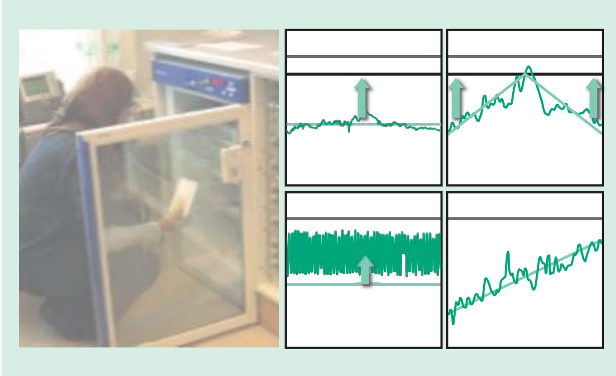

Fig. 6—Temperature-controlled Facilities at Hospital (Freezer) and Example of Feature Classification of Temperature Data.
Data from each temperature-controlled facility is collected via a wireless network. The data is classified based on usage and dynamic characteristics that vary from day to day.

DYNAMIC RESOURCE ALLOCATION

As these hospitals grow in size, the factors important to improving efficiency extend beyond just the medicine

Fig. 7—Ethnographic Analysis in Progress at Bispebjerg and Frederiksberg University Hospital.
Hitachi undertook an ethnographic analysis of doctors, nurses, and other staff in collaboration with Bispebjerg and Frederiksberg University Hospital.

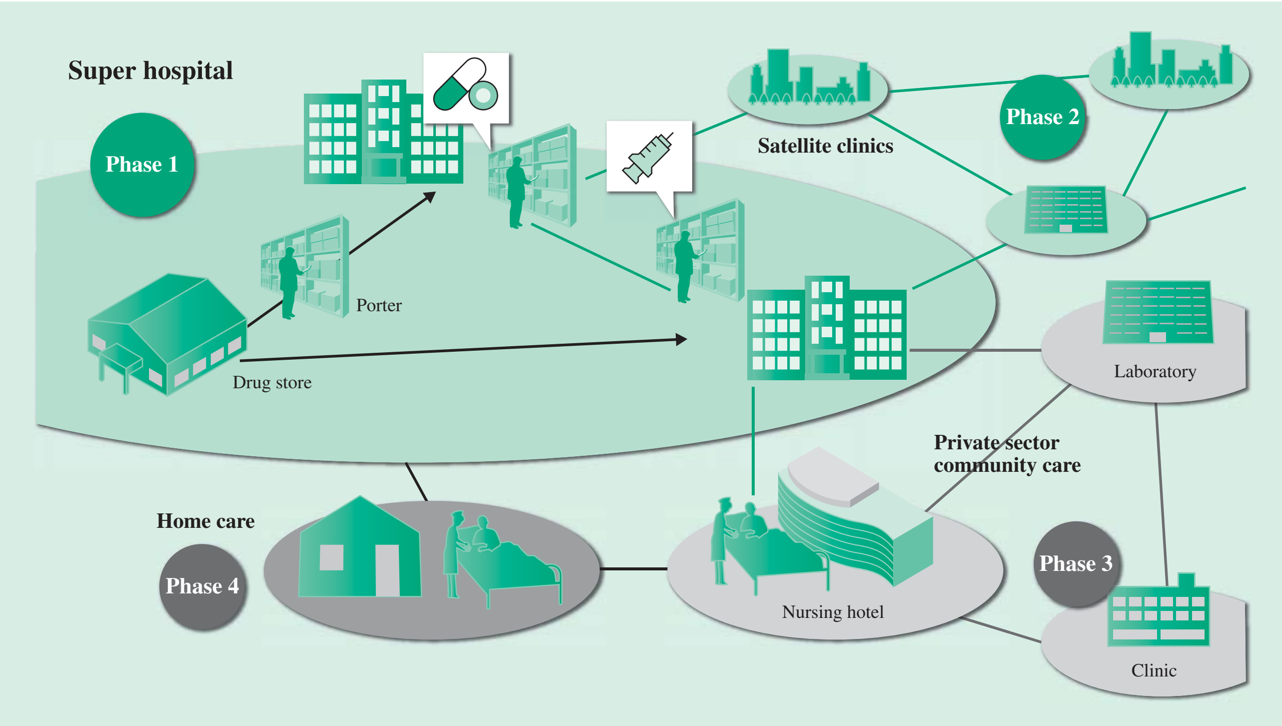

Fig. 8—Dynamic Resource Allocation.
The diagram shows how the dynamic distribution and disposition of resources is used to improve efficiency as these hospitals grow in size. To allow for future enhancements, consideration is also given to extending the practices outside the hospital.

or food stored in temperature-controlled facilities. They also encompass the dynamic distribution and disposition of resources that include staff, medical devices, and other medical supplies. As human resources are of the utmost importance, particularly in hospitals, the challenge is to maintain an awareness of the location and movement of people and to ensure that these movements are appropriate given changing circumstances. Furthermore, when a hospital plays a central role in community healthcare, there is a need to consider how to handle the sharing of resources with the private sector, including general practitioners (GPs). In this case, the methods adopted need to be able to work with the different systems already in place at external organizations (see Fig. 8).

Controlling the Flow of People and Devices

Hitachi has engaged in a variety of research and development relating to the measurement and analysis of human behavior over many years. This includes techniques for using sensors to locate people within an area and track their movements, and for measuring people's location and the forms of communication they engage in (time spent in conversation, acceleration data, etc.) to calculate indices for things like activity level, initiative, or time spent concentrating[10].

At the Bispebjerg and Frederiksberg University Hospital, it was estimated that staff wasted 20 steps a day in their movements. Along with using sensor measurements of their movements to identify this waste in more detail, an analysis of the causes is conducted using information about their jobs (whether they are a doctor or nurse) and the work to which they are assigned. The movement characteristics obtained from this analysis are then utilized to optimize the layout of rooms and other facilities at the new hospital construction project currently in progress (see Fig. 9).

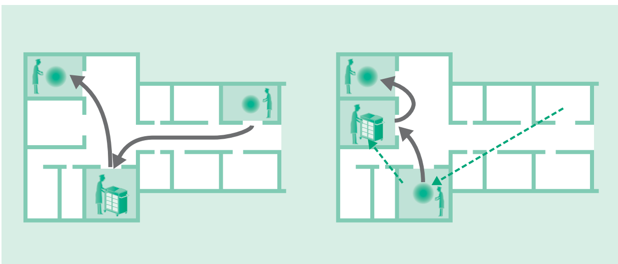

Fig. 9—Analysis of People's Movements at Hospital and Building Layout Optimization.
The layout of rooms and other facilities at the new hospital construction project currently in progress is optimized using movement characteristics identified by an analysis of the flow of people.

By attaching sensors not just to people but also to beds, lifts, and other medical equipment, it is possible to eliminate waste in the use of scarce and expensive equipment and facilitate dynamic resource allocation whereby the ideal location for bringing together staff, equipment, and other medical supplies can be determined on the fly.

Autonomous Decentralized Systems

Based on ideas from living organisms, autonomous decentralized systems are total systems that integrate individual subsystems, analogous to the way a human body is constructed from cells. A feature of autonomous decentralized systems is that, because each subsystem operates autonomously, the overall system can continue to function even if some subsystems fail, or similarly if new subsystems are added. Currently, such systems are being further enhanced to provide the ability to reallocate resources between them, such that even systems intended for different purposes will be able to connect together to the extent that is compatible with their serving their respective purposes[11] (see Fig. 10).

A feature of the super hospital concept is that a number of existing hospitals will merge to form a new expanded and enlarged facility. The Bispebjerg and Frederiksberg University Hospital, for example, is the result of merging Bispebjerg Hospital and Frederiksberg Hospital, and is scheduled to undergo a staged program of new construction, relocation, and refurbishment over the period from 2014 to 2025. This will involve progressive expansion and growth, starting from the base of existing operations and systems. The facility will also be called on to become a hub for community healthcare in the future, expanding the scope of healthcare service coverage by linking together the information and activities of different organizations, including satellite clinics, GPs and other private sector providers, and ultimately families providing care in the home, as shown in Fig. 8.

As this expansion and integration will involve the organizations continuing to use their existing systems, it is an embodiment of the idea of an autonomous decentralized system in which subsystems intended for different purposes are able to share resources between them.

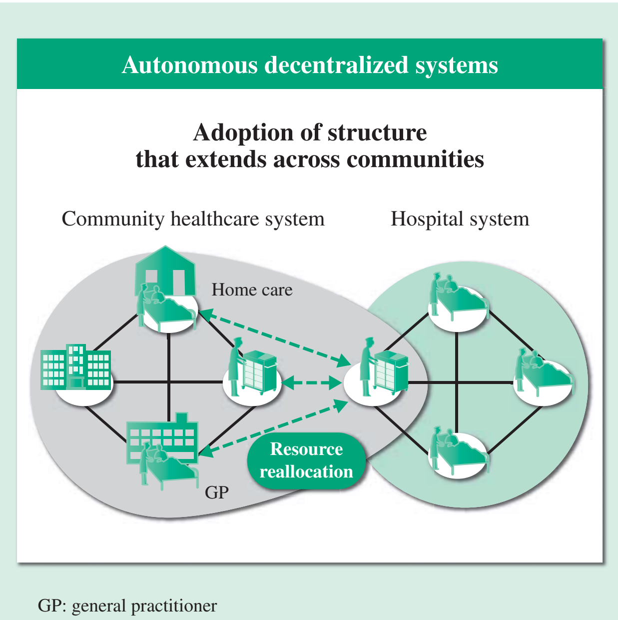

Fig. 10—Use of Autonomous Decentralized Systems for Expansion into Community Healthcare.
By adopting structures that extend across communities, it is possible to connect together even systems intended for different purposes to the extent that is compatible with their serving their purposes, and to reallocate resources between them.

CONCLUSIONS

To find rapid solutions to the challenges that face mature societies, Denmark has adopted innovation as a key component of its national strategy. Along with its innate national characteristics, Denmark is focusing on initiatives such as education to improve IT literacy to facilitate participatory innovation, and has great potential as a test bed for assessing the value of new technologies and solutions in practical use.

Hitachi is currently participating in the super hospitals initiative and is working to establish new service concepts with the aim of improving the efficiency of management at the new huge hospitals by 25%. In the future, Hitachi also intends to engage in collaborative creation with customers and other partners who are taking the lead in dealing with the challenges of energy and the environment and transportation that have been identified as priorities by the government of Denmark.

Regardless of the field, and unlike in developing economies where social infrastructure can be built from scratch and on a large scale, the provision of social infrastructure in mature societies involves working from a base of existing systems that already have designated functions and that operate in an autonomous and decentralized fashion. Hitachi believes that the technologies it has built up in Japan, such as those for autonomous decentralized systems, will prove effective for this purpose.

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Category Overview

Product Innovation Achieved through Technology Innovation
—Center for Technology Innovation—

ROLE OF CENTER FOR TECHNOLOGY INNOVATION

FORMED from parts of the Hitachi Research Laboratory, Yokohama Research Laboratory, and Central Research Laboratory, Hitachi's nine Centers for Technology Innovation respectively work in the fields of Energy, Electronics, Mechanical Engineering, Materials, Systems Engineering, Information and Telecommunications, Controls, Production Engineering, and Healthcare. In addition to developing Hitachi's technology portfolios further in these nine sectors through the creation of innovative products, the centers will also support the development of new solutions through the optimal combination of a wide range of technologies.

STRENGTHENING OF TECHNOLOGY PLATFORM

In parallel with Hitachi's more than 100-year history of product development, its Research & Development Group has been developing and accumulating element technologies that underpin fundamental product features such as performance and reliability. In the future, Hitachi plans to develop these technologies further and organize them into technology platforms so they can be utilized in the development of innovative products and services that will ensure ongoing growth.

A technology platform collates together a variety of element technologies. These cover all of the processes from basic research to product development, including

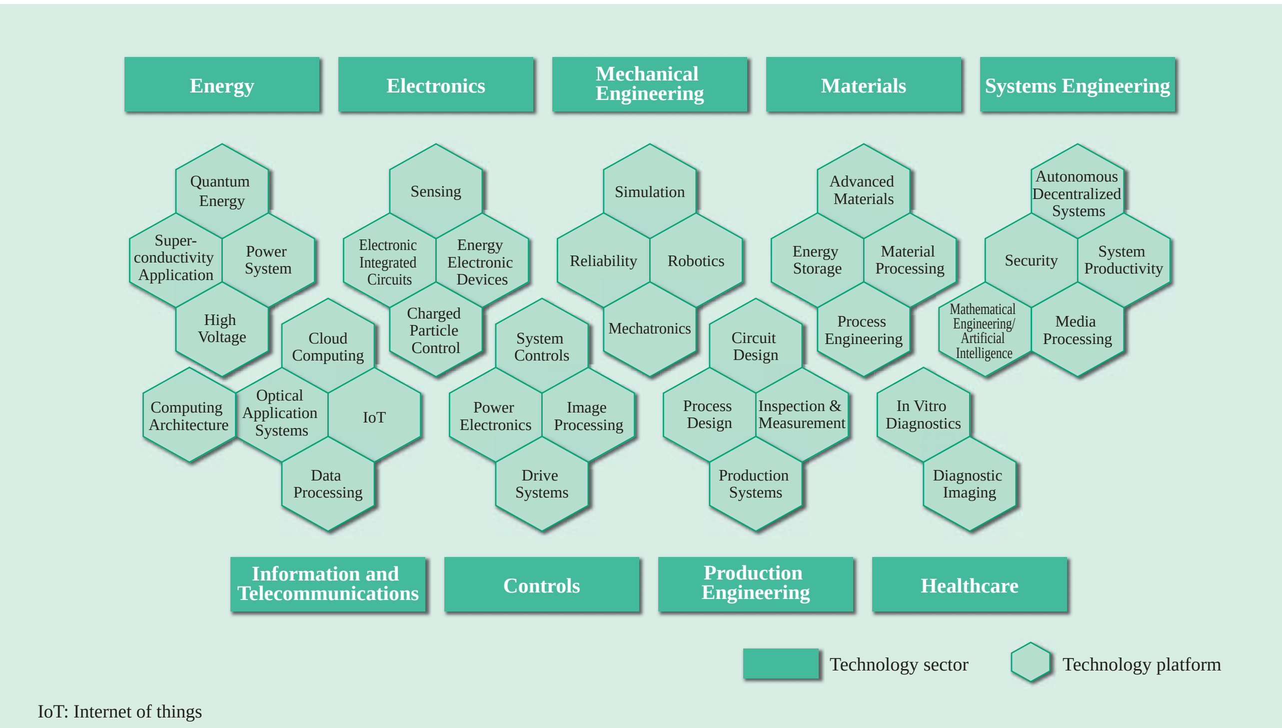

Fig. 1—Technology Sectors and Technology Platforms.
Hitachi has brought together existing element technologies and combined them into 36 technology platforms (represented by the honeycomb cells in the figure) covering nine technology sectors, including Energy and Electronics.

core technologies developed in-house, technologies adopted from external sources, and experimental research technologies for testing the limits of theory. Hitachi has already established numerous technology platforms through its ongoing work on element technology development, product applications, and enhancements.

This resource is currently organized into 36 technology platforms spread across nine technology sectors (see Fig. 1). Along with coordinating its technology platforms with product development and deepening their scope, Hitachi is also expanding them in step with international technology trends.

USE OF TECHNOLOGY PLATFORMS TO CREATE INNOVATIVE PRODUCTS

This section groups the establishment of technology platforms and the development of innovative products into four categories and describes example developments.

Technology Innovation Coordinated with Product Development

Hitachi develops new technologies as it seeks to obtain "ultimate performance" from products. The critical dimension scanning electron microscope (CD-SEM) provides a typical example (see Fig. 2). Since commencing research in 1982, Hitachi has continued to improve resolution to keep pace with advances in semiconductor device miniaturization. Along with higher resolution, Hitachi has also developed new measurement techniques that go beyond the limit of optical wavelength resolution. In the case of electron beam sources (electron guns), which are an important determinant of measurement performance, Hitachi has been working first on field emission electron guns and subsequently on the Schottky electron gun, which provides more stable emission of electrons, and has commercialized these by utilizing electromagnetic field analysis techniques for electron beam manipulation. The achievement of highly stable electron emission and high resolution has improved resolution from 15 nm initially to 1.8 nm. Thanks to these ongoing technology innovations, Hitachi now has the largest share of the global market for CD-SEMs[*1].

Fig. 2—CD-SEM for Use in Semiconductor Production.
This is a photograph of the CG5000 high-resolution field emission beam critical dimension scanning electron microscope (FEB CD-SEM) (Hitachi High-Technologies Corporation). The CG5000 is used for the dimensional measurement of the patterns formed on semiconductor or other wafers.

Finger vein authentication provides another example. With the aim of obtaining "ultimate performance" from security techniques that use biometric information, Hitachi has developed a biometric identification technique capable of high-speed recognition of finger vein patterns regardless of how the finger is presented (position and orientation, etc.). The technology is currently being deployed for walkthrough-style personal verification.

This issue of *Hitachi Review* includes an article about energy-efficient room air conditioners that offer yet another example. These have achieved an Annual Performance Factor (APF) of 7.3 thanks to the use of analysis techniques to make ongoing improvements to the efficiency of system components, leading to the air conditioner winning the FY2014 METI Minister's Prize for Excellence in Energy Efficiency and Conservation.

Creation of Innovative Products by Combining Different Technologies

Work is ongoing to achieve innovation in numerous products through the combination of different technologies, elevators being one recent example. This has included developments in fields that have been a subject of research at Hitachi since 1920, including drive and control techniques for electric motors with high output intended for high-speed transportation, and heat-resistant materials for brakes that can perform an emergency stop when excessive speed is

*1 As of April 2015, based on research by Hitachi, Ltd.

Fig. 3—Hitachi High-speed Data Access Platform[*3]*.*
Centered around the ultrafast database engine, the platform contributes to the use of big data by enabling ultra-high-speed data searches.

Fig. 4—Shipment of Class 800 Rolling Stock for the UK. Department for Transport Intercity Express Programme (IEP).
Hitachi successfully complied with European standards by taking analysis techniques and material technologies built up through product development in a variety of fields and applying them to rolling stock safety design.

detected. Along with faster speeds there is also a need for comfort. Hitachi has developed the world's fastest elevator[*2] with a speed of 1,200 m/min by combining the above technologies for high-speed operation with active damping techniques that can detect tiny distortions in guide rails or lateral vibration caused by wind and reduce the associated vibrations, and techniques for controlling the air pressure in elevators cars to minimize ear blockages.

Other examples are hybrid analyzers for clinical chemistry and immunoassay. These are capable of performing a wide range of biochemical and immunological blood tests at high speed thanks to the combination of optical measurement techniques designed for high sensitivity with techniques for the precise separation of samples, including micro-sampling methods and sample handling techniques.

As an example of this sort of technology, this issue of *Hitachi Review* includes an article about amorphous motors. Through a combination of motor design techniques and machining techniques for amorphous metals, which are characterized by low energy losses, the motors have achieved the highest possible International Efficiency (IE) rating of IE5.

Technology Innovations Achieved through Infusion of Open Innovation

There are also cases of product innovations that resulted from the adoption of new technologies through collaboration with external institutions and their combination with Hitachi technologies.

One example is the ultrafast database engine[*3], which serves as the core of information systems. Major improvements in processing performance have been achieved by combining database implementations that Hitachi has built up through the mainframe era with the principle of out-of-order execution devised by Professor Masaru Kitsuregawa and Associate Professor Kazuo Goda of The University of Tokyo. The increasing speed of data processing makes it possible to optimize the use of hardware performance. This also significantly reduces the execution time for

*2 As of June 2015, based on research by Hitachi, Ltd.
*3 Utilizes the results of "Development of the Fastest Database Engine for the Era of Very Large Database and Experiment and Evaluation of Strategic Social Services Enabled by the Database Engine" (Principal Investigator: Prof. Masaru Kitsuregawa, The University of Tokyo/Director General, National Institute of Informatics), which was supported by the Japanese Cabinet Office's FIRST Program (Funding Program for World-Leading Innovative R&D on Science and Technology).

big data analytics (see Fig. 3).

The proton beam therapy system for cancer treatment described in an article in this issue of *Hitachi Review* combines Hitachi's spot scanning technique with the tumor tracking technique developed at Hokkaido University[*4]. This is able to target the proton beam accurately even at tumors that move due to the patient's breathing, for example.

Cross-disciplinary Creation of Innovative Products

Hitachi is taking technologies built up through product development in one sector and utilizing them in different sectors, not only to create innovative products, but also to expand and strengthen its technology platforms.

An example of this is the safety design of the Class 800 series high-speed rolling stock for the UK's Intercity Express Programme (IEP). This involved the application to high-speed rail safety design of analysis techniques and material and other technologies developed for fields such as industrial machinery, and nuclear and thermal power generation. The rolling stock achieved compliance with the numerous European safety standards through measures that included the design of crashworthy structures and the simulation of collisions involving an entire train, something that is difficult to test experimentally. The first train was shipped to the UK from Kasado Works, Hitachi, Ltd. in March 2015. Operation is scheduled to commence in 2017 (see Fig. 4).

Other examples include the big drum washer-dryer, which includes a "wind iron" technique for blowing air through clothing to remove wrinkles and that was developed using a blower design that re-purposed techniques from fluid dynamics developed for the design of the Shinkansen, and a power module with double-sided cooling that puts technology developed for small automotive inverters to use in uninterruptible power supplies.

CONCLUSIONS

Unlike the individual element technologies, technology platforms are not something that can be assembled overnight. Along with the further development of its technology platforms, the Research & Development Group intends to continue working on innovations in the technologies and products that use these platforms.

*4 Utilizes the results of "Advanced Radiation Therapy Project: Real-time Tumor-tracking with Molecular Imaging Technique" program (Principal Investigator: Professor Hiroki Shirato of the Graduate School of Medicine, Hokkaido University) that ran from March 2010 to March 2014 under the Japanese Cabinet Office's FIRST Program.

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Featured Articles

Image Recognition Technology that Helps Save Energy in Room Air Conditioners

Yuto Komatsu
Koichi Hamada, Ph.D.
Yoshiaki Notoya
Kotoyoshi Kimura

OVERVIEW: Room air conditioners need to be energy efficient, accounting as they do for a significant proportion of household power consumption. In addition to achieving industry-leading energy efficiency in the 4.0-kW, 5.6-kW, and 8.0-kW classes, room air conditioner launched in FY2014 also features the three-way front flap function that uses image recognition both to save power and improve comfort. Multi-monitoring system uses a near-infrared camera together with visible-light and thermal imaging cameras not only to identify the location of people and measure the surrounding temperature, but also to determine the location and shape of furniture and the room layout. The air conditioner provides comfortable heating and cooling throughout the year through fine-tuned control of air flow, including avoiding furniture and directing the flow of warm air toward people's feet when used for heating, and circulating cool air to lower the temperature of the entire room when used for cooling.*

INTRODUCTION

HOME appliances have evolved over time to satisfy demands for entertainment, convenience, and comfort, and to adapt to changes in society and the environments in which people live. Recent years have seen strong demand for more sophisticated functions, user interfaces that make appliances easier to use, and energy efficiency. The way in which home appliances have evolved can be broadly divided into the following two trends.

(1) Entertainment

The trend toward providing information, entertainment, and the enjoyment of life, starting with radio, television, and audio equipment

(2) Convenience

The trend toward washing machines, refrigerators, and other home appliances intended to make life more convenient by, for example, cutting the amount of time spent on housework

Furthermore, along with the higher living standards made possible by home appliances, comfort is now emerging as a third major trend thanks to the arrival of home appliances that operate entirely on electric power and advances in air conditioners that provide more comfortable living spaces[1]. Comfort means the optimal control of conditions like temperature and humidity, and providing a near-natural environment. The purpose of integrated air conditioners is to create comfortable air-conditioned living spaces like this. To design air conditioners that can provide comfort by satisfying various criteria, such as coping with seasonal temperature variations, differences in climate from Hokkaido to Okinawa, and highly airtight houses, air conditioner manufacturers have been developing energy-efficient technologies.

SENSING TECHNOLOGIES FOR ROOM AIR CONDITIONERS

As progress has been made on the development of energy-efficient technologies, air conditioner manufacturers have released models that offer more sophisticated functions and that achieve energy-efficient operation by controlling the direction and volume of air flow using technologies such as thermal detection sensors (thermopiles) and infrared sensors (pyroelectric sensors) to detect people entering or leaving the room and to collect information on aspects like the number of people in the room, where

* As of April 1, 2015. The power consumption during a period of operation is 1,036 kWh for the RAS-X40E2, 1,630 kWh for the RAS-X56E2, and 2,802 kWh for the RAS-X80E2, measured under Japanese Industrial Standards (JIS) conditions.

they are, and their level of activity. Along with more sophisticated functions, these air conditioners now also require technologies for detecting the location of walls, linear features, doors, furniture, and other aspects of the room layout, and for performing detailed control of air flow direction and volume.

The following three main methods can be used to detect furniture and other aspects of the room layout.
(1) Using multiple cameras
(2) Using ultrasonic sensors
(3) Using lasers

The method involving multiple cameras uses the differences between images from different cameras to determine the locations of objects. Problems with this approach include the high cost of using a number of cameras and the restrictions it imposes on where cameras are located and the size of the camera housings. Although the use of an ultrasonic sensor overcomes the cost problem, this method suffers from poor accuracy and poor detection range due to the limited amount of information the sensor is able to obtain. The problems with using a laser, meanwhile, include cost and safety[(2)].

Accordingly, to satisfy both cost and accuracy requirements, Hitachi embarked on researching and developing a technique for detecting room layout and furniture using a single camera[(3), (4)]. The resulting technique uses a structural model of the room provided in advance to detect room layout and furniture from architectural information obtained from a single image, such as when doors are open or closed and the location of objects. In anticipation of the technique being used in home appliances, Hitachi also developed methods that could be implemented with a low computational load.

To provide a technique for achieving both energy efficiency and greater comfort, Hitachi was the first to use a visible-light camera as a sensor in an air conditioner, developing the multi-monitoring system function, which detects the movement of people in the living space to control comfort and energy use based on the actual circumstances. The function was included in the air conditioners it released in FY2012.

In FY2013, Hitachi succeeded in making the energy efficiency feature more accurate and comfortable by developing the enhanced multi-monitoring system function for sensing the room layout using a thermal imaging camera (thermopile) in addition to the visible-light camera. This function automatically controls the direction and volume of air by using the images captured by the cameras fitted in the room air conditioner to detect furniture and determine the room shape, when doors are open or closed, and so on. In a home that has an additional room adjoining the living room, for example, it can automatically perform air conditioning for the living room only when the connecting door is closed and for both rooms when the door is open. It can also automatically control the variable-direction (“swing”) of blowing air based on the room size.

For the FY2014 product range, Hitachi developed new multi-monitoring system. This is a further enhancement of the FY2013 models’ function that is designed not only for energy efficiency but also for a level of comfort that will obtain a sympathetic response from users. The FY2014 models not only determine the location of people and the surrounding temperature but also detect the location and shape of furniture and other aspects of the room layout to identify how air flows through a room. The following sections 3 and 4 provide detailed explanations of two image recognition technologies developed for use in air conditioners. The first technology is used for detecting the room layout, and the second technology is used for detecting furniture.

ROOM LAYOUT DETECTION TECHNOLOGY

Because past room air conditioners have been unable to detect things like the size and shape of the room and whether doors are open or closed, they have not been able to adjust air flow to accommodate the room layout, such as by boosting output to the most distant parts of the room[(5)].

To overcome this problem, Hitachi developed a technology for determining room layout. The technology works by identifying the movement and location of the structural elements of the room, including walls, floor, linear features, and doors. Its ability to detect the location of doors and whether they are open or closed means that a single air conditioner can, for example, direct a strong flow of air to the farthest corners of a room, even in cases where there are two adjoining rooms.

How Room Layout Detection Works

This research included the development of a technology for determining room layout from camera images of a room’s doors, corners, and other features in order to achieve a uniform air temperature throughout the room. By using the technology to identify doors and corners, it is possible to direct a strong flow of air to

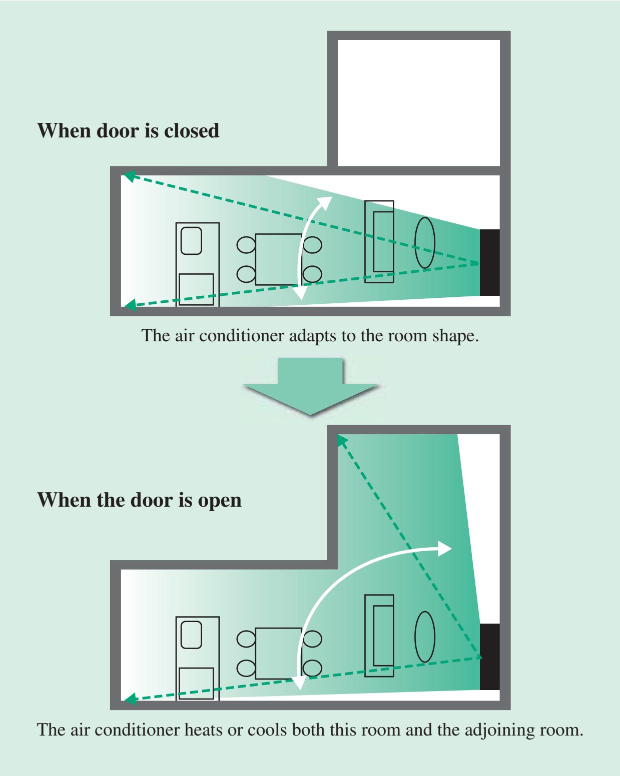

Fig. 1—Room Layout Detection Example.
Swinging (varying the direction in which air is blown from side to side) provides tight control over the volume of air reaching the back of a room while also preventing air flow from being blocked by walls and maintaining a uniform temperature throughout the room.

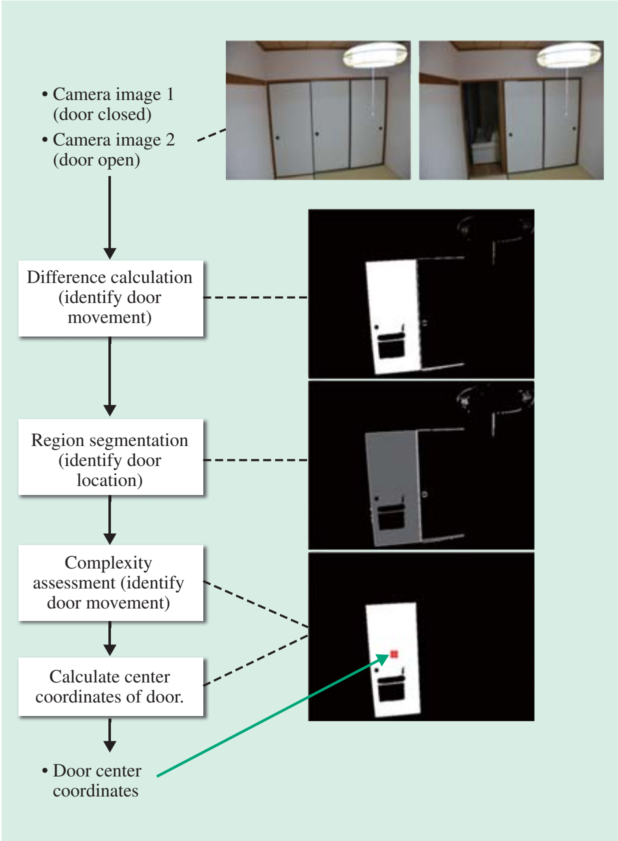

Fig. 2—Sequence of Steps for Door Detection.
The technology identifies a number of possible doors in camera images and then narrows these down to determine which ones are in fact doors.

the farthest corners of a room, or to an adjoining room, by directing the air flow toward the corners only.

Fig. 1 shows an example of how this room layout detection technique is used. Swinging the direction in which air is blown from side to side provides tight control over the volume of air reaching the back of the room while also preventing air flow from being blocked by walls and maintaining a uniform temperature throughout the room.

To determine room layout, it is necessary to identify the location of doors. This is done by identifying a number of possible doors in the camera images and then narrowing these down to those that are in fact doors. This procedure is able to identify doors rapidly. Fig. 2 shows the sequence of steps for detecting a door. The first step is to calculate the differences between an image in which the door is open and one in which it is closed so as to identify the movement of an opening or closing door. Next, a region segmentation process is applied to the calculated differences to identify possible doors. These candidates are then assessed for characteristics like size and squareness of shape until there is only one candidate left. A complexity value (indicating the complexity of the color pattern across the entire surface of the door) is then calculated for the identified door and this is used to determine whether the door is open or closed. Finally, the centerpoint coordinates of the door are calculated from its area.

To detect the architectural structure of the room, it is necessary to identify the linear features of the building accurately. The new technology uses information about the structure of the room provided in the form of a model to identify which of the numerous possible linear features in the room are in fact structural and determine the building structure based on where these intersect. The structural information about the room (model) consists of the angles and positions at which lines intersect and how clearly the lines are visible. This is used to narrow-down possible linear features and identify the corners of the room.

Fig. 3 shows the sequence of steps for detecting corners. First, the edges present in camera images are detected to identify potential linear features. Next, a line detection technique is applied to the images

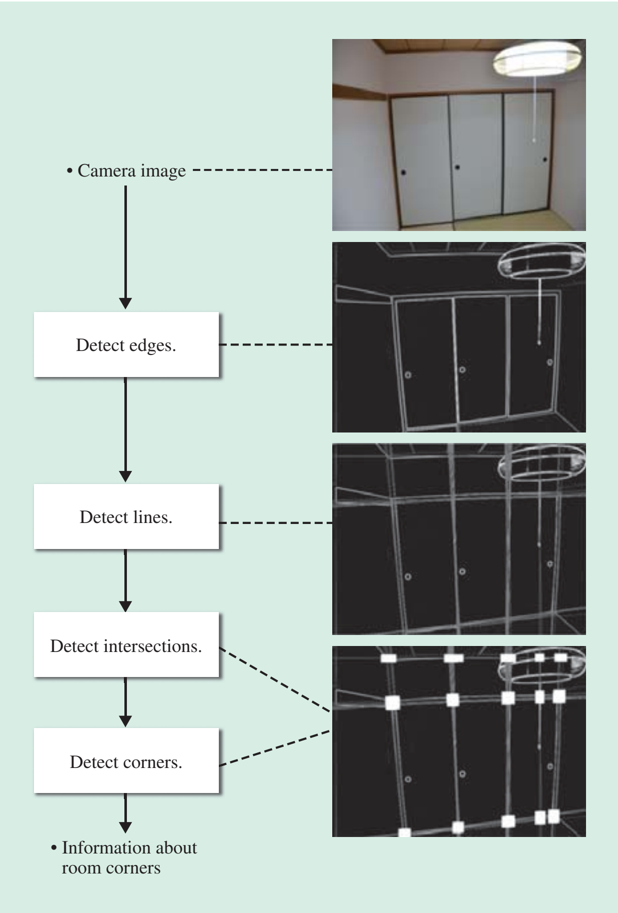

Fig. 3—Sequence of Steps for Corner Detection.
Structural linear features are identified from a large number of candidates and the room's structure determined from the intersections between these.

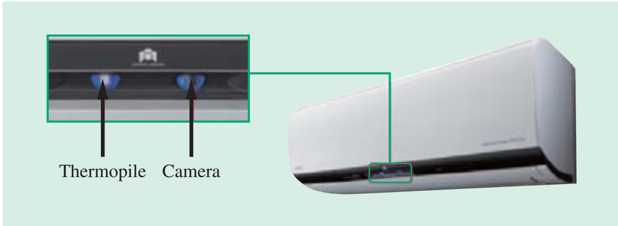

Fig. 4—Camera Mounted on Air Conditioner.
The thermopile and camera are located on the front of the air conditioner, as shown.

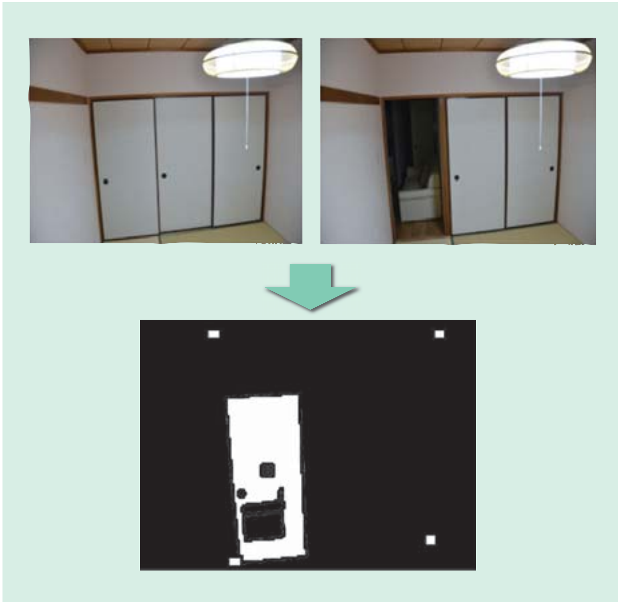

Fig. 5—Operation of Room Layout Detection.
This shows the operation of room layout detection in practice using a data set of images from a camera mounted on an air conditioner.

containing detected edges to narrow-down the number of potential linear features. Finally, the predefined structural model of the room is used to determine which of the many potential linear features are in fact structural, and the intersections between these are used to determine the room's structure.

Results of Real-world Testing of Room Layout Detection

Testing was conducted to evaluate the performance of room layout detection in a room air conditioner. The testing used a data set of images from a camera mounted on an air conditioner (see Fig. 4). Fig. 5 shows an example of room layout detection being used.

FURNITURE DETECTION TECHNOLOGY

The most common layout for Japanese homes includes a living, dining, and kitchen area in which a single large room air conditioner is installed and used extensively. This area is characterized by being a place where family members congregate and is the scene of various different activities at different times of the day. The living area differs from other rooms in that it contains furniture such as a sofa or dining table, and feedback from customers indicates that this furniture can block air flow and prevent warm air from reaching their feet, or that temperature variations occur such that only parts of the room are cooled. In response to these issues, Hitachi developed a furniture detection technique that determines the location and shape of furniture and identifies the pathways through which air flows across the room.

Sequence of Steps for Furniture Detection

A camera is fitted on the front of the indoor unit of the air conditioner. It is able to operate as a near-infrared camera by using a shutter mechanism to place a filter

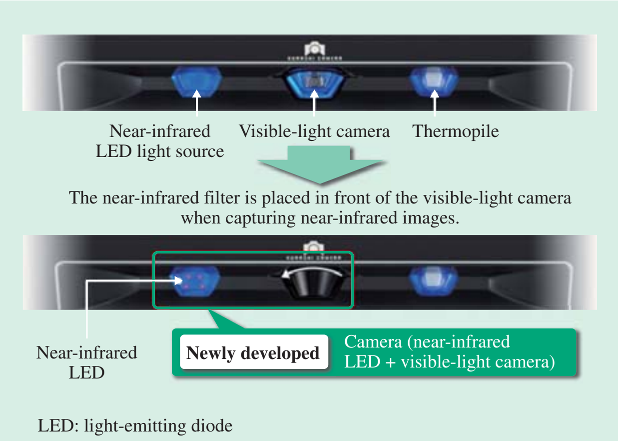

Fig. 6—Multi-monitoring System Components.
A filter transparent to near-infrared light is placed in front of the visible-light camera (middle) when needed to obtain near-infrared images.

in front of the central visible-light camera that allows near-infrared light to pass when needed. In this case, a near-infrared light-emitting diode (LED) is used to illuminate the scene so that an image can be acquired (see Fig. 6).

The resulting near-infrared image is then subjected to a variety of processing, including noise cancellation, edge detection, and region segmentation to identify potential items of furniture. Next, the features of the furniture (such as shape and size) are used to narrow down the number of candidates. The length of the furniture legs and the area of openings through which air can flow are then calculated to determine whether or not each item of furniture will block air flow (see Fig. 7).

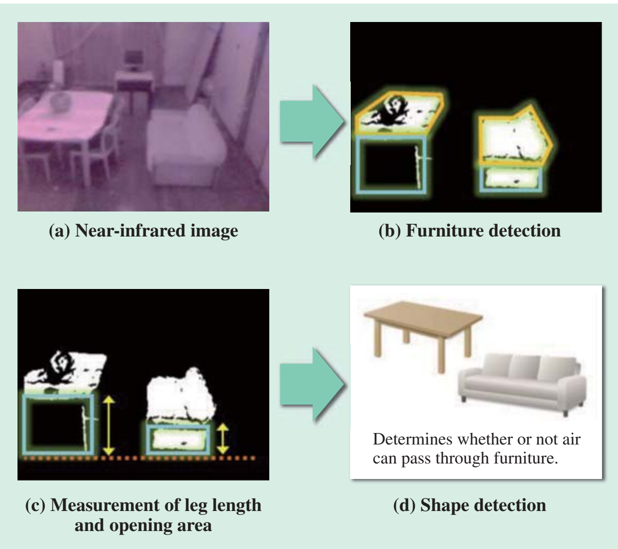

Fig. 7—Furniture Detection Using Near-infrared Images and Image Processing.
Furniture features (shapes) are identified using edge processing and pattern recognition. This also differentiates between furniture through which air can and cannot pass.

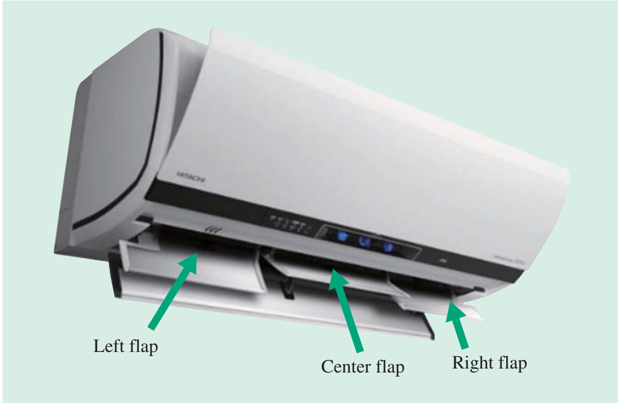

Fig. 8—Three-way Segmented Front Flap.
Each of the three flap segments can be positioned independently to provide fine-tuned control of air flow direction.

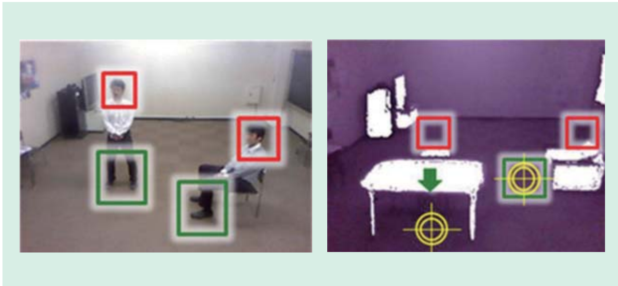

Fig. 9—Detection of People's Feet (Left) and Detection of Air Flow Paths when Heating (Right).
This uses the visible-light camera to detect people's feet and the near-infrared camera to determine how air flows through the room.

To control the flow of air from the indoor unit to the air flow paths identified by this process, Hitachi developed a three-way segmented front flap (see Fig. 8). Whereas previous models had two continuous flaps to direct air flow, the upper flap on this new design is split into three segments. This provides finer control over the direction of air flow and allows air to be directed toward these paths, ensuring comfortable air conditioning by directing warm air toward people's feet when heating and circulating the air when cooling in a way that minimizes the buildup of pockets of cool air.

Furthermore, Hitachi also developed a foot detection technique that uses the visible-light camera to enable the detection of people's feet, regardless of their temperature or what they are wearing (slippers or thick socks, for example) (see the left side of Fig. 9).

Results of Real-world Testing of Air Flow Path Detection

The right-hand image in Fig. 9 shows how the above information is used to identify where air needs to be blown in order to reach people's feet when heating.

CONCLUSIONS

This article has described room layout detection and furniture detection technologies for room air conditioners that use image recognition and were developed with the aim of providing both energy efficiency and comfort.

Room layout detection detects the size and shape of the room and determines whether doors are open or closed from images captured by a camera fitted onto the air conditioner. Using this information it automatically controls the volume and direction of air based on conditions in the room. Furniture detection, meanwhile, determines the position and shape of furniture and other aspects of the room layout, and identifies how air flows through the room, enabling fine-tuned control of air flow direction to blow warm air toward people's feet (when heating) or circulate cool air to lower the temperature of the entire room (when cooling). This fine-tuned control of air flow direction improves energy efficiency while maintaining comfort by preventing pockets of higher temperature from forming.

These technologies were developed with a view to their use in home appliances, using images from a single camera, and capable of being implemented with a low computational load. In the future, Hitachi intends to investigate other applications, including spatial detection and obstacle identification when operating mobile robots, or detection of abnormal situations in buildings or structures (such as offices, stores, or tunnels).

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Featured Articles

Biometric Authentication Platform for a Safe, Secure, and Convenient Society

—Public Biometrics Infrastructure—

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Yusuke Matsuda
Kenta Takahashi, Ph.D.
Akio Nagasaka, Ph.D.

OVERVIEW: With the rise of issues such as cyber-crime and terrorist threats that have accompanied the growing use of information technology, biometric authentication has attracted attention as a means of identifying individuals to ensure security. However, biometric authentication is mainly used by individuals or individual organizations, and it has not reached a stage where it is available for widespread use as part of the infrastructure of society. This article considers the challenges associated with the wider use of biometric authentication as a basis for authenticating identity in social infrastructure, and describes the public biometrics infrastructure (PBI) and walkthrough-style finger vein authentication technology that can overcome these challenges. These technologies can be used to create a society with "empty-handed" safety and security.

INTRODUCTION

CORPORATE use of cloud computing and other forms of information and communication technology (ICT) is growing along with the adoption around the world of technology like national identity (ID) systems and electronic systems for government services, but accompanying these developments has been a rise in the damage done by cyber-crime. Meanwhile, the importance of physical security in cities is increasing as various countries face increased terrorist threats. Identity authentication to prevent unauthorized access or spoofing is a core technology for use in security for social infrastructure, which includes cyber and physical systems such as these. Among the technologies for authenticating identity, biometric authentication has attracted attention for its ability to combine a high level of both security and convenience. Biometric authentication is a way of confirming the identity of a person by acquiring information on their biological or behavioral characteristics, such as their finger veins or fingerprints, and comparing it against stored data. It provides a very convenient way to verify identity, with a lower risk of identification information being lost, stolen, or forgotten compared to conventional methods like passwords and smartcards. The use of biometric authentication to provide the basis for identity authentication in various services associated with social infrastructure makes possible a society in which safety and security can be achieved with an "empty-handed" style, without the need for smartcards or passwords.

However, three challenges in particular will need to be overcome if biometric authentication is to become a more widely used part of the social infrastructure. These are: getting various different services to adopt a sharable platform, ensuring the privacy and security of biometric information, and improving the convenience of authentication.

(1) Sharing a platform among various different services

Biometric authentication systems in current use ensure security by managing the biometric information in a standalone system. The problem with this model is that, when biometric authentication systems are used by a variety of different services, each system needs to record its own biometric information. And because this need to record information is one of the obstacles to wider use of biometric authentication, getting a wide variety of different services to adopt it as a means of verifying identity will require the development of a sharable authentication platform that these services can all use.

(2) Ensuring the use of biometric information

Because biometric information is of a sensitive nature, with the potential to identify a person's race, ethnicity or state of health, for example, it needs to be kept secure to maintain privacy. Furthermore, because one's biometric information is a lifelong attribute that cannot be discarded or updated, it is very difficult to restore security once leaked, being vulnerable to use in forgery, replay attacks*1, or other forms of spoofing. Preventing leaks of biometric information is essential to protect users from such security threats.

(3) Improving the convenience of authentication

If biometric authentication is to be made a routine part of the social infrastructure, its use must not impose inconvenience. Accordingly, its operation must be sufficiently intuitive, easy-to-understand, and simple enough that anyone will be comfortable using it. For use in public places where large numbers of people congregate, such as major event venues or large facilities like railway stations or office buildings, the technology must combine both the accuracy needed to reliably identify individuals and the high throughput needed to ensure a smooth flow of people without queuing.

To deal with the first and second challenges of shared use and of privacy and security, Hitachi has put forward the concept of a public biometrics infrastructure (PBI) and implemented it by developing biometric signature technology(1), (2). Hitachi is also working on the research and development of walkthrough-style finger vein authentication technology to overcome the third challenge of improving convenience(3).

*1 An attack involving the interception of authentication data such as a user identity (ID) and password and its use for spoofing.

PUBLIC BIOMETRICS INFRASTRUCTURE (PBI)

This section describes the concept of a PBI(1) that is intended to realize a sharable authentication platform across a variety of services and ensure the privacy and security of biometric information, and its implementation in the form of biometric signature technology(2).

Problems with Existing Biometric Authentication

Existing biometric authentication works by storing the biometric information obtained from users when they register and then using this information to confirm their identity by comparing it against the information obtained at the time of authentication. Biometric authentication systems can be broadly divided into a number of different models based on where they store and check the biometric information (see Fig. 1). The following section gives an overview of these models and describes the problems associated with each of them.

(1) Perform authentication in a smartcard

This involves storing the biometric information in a smartcard, such as the debit cards used in bank automated teller machines (ATMs). Storing the biometric information in a secure region on the smartcard enables robust security. However, because it requires smartcards to be issued to users, and that users have the smartcard with them when

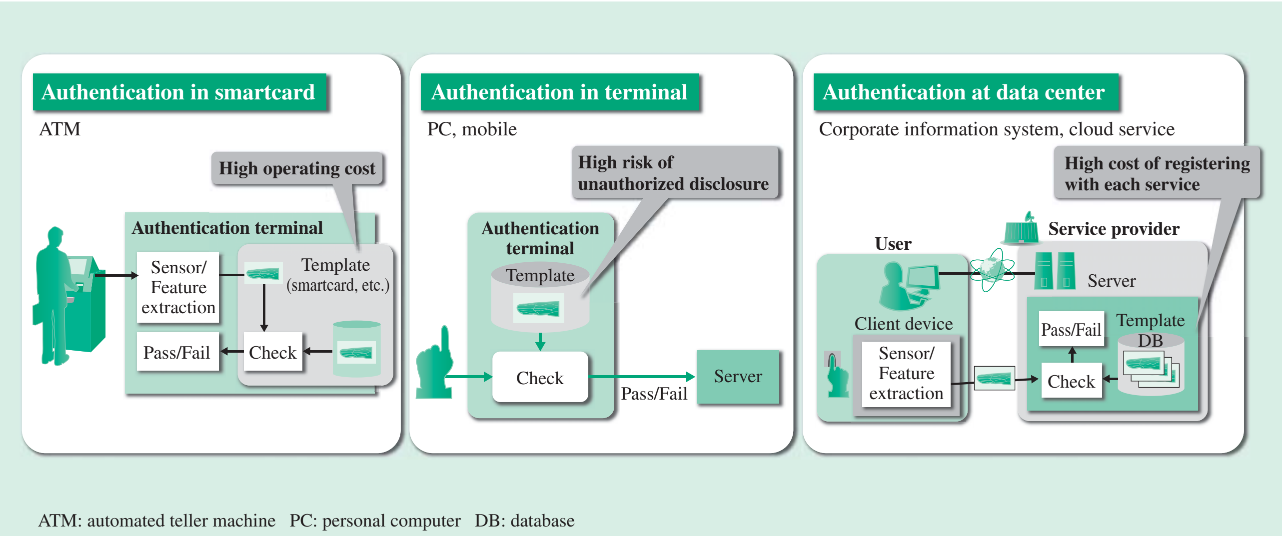

Fig. 1—System Model for Biometric Authentication.

The three existing system models for biometric authentication involve performing authentication in the smartcard, in the terminal, or at the data center. All of these suffer from problems that include operating costs, risk of unauthorized disclosure, and registration costs.

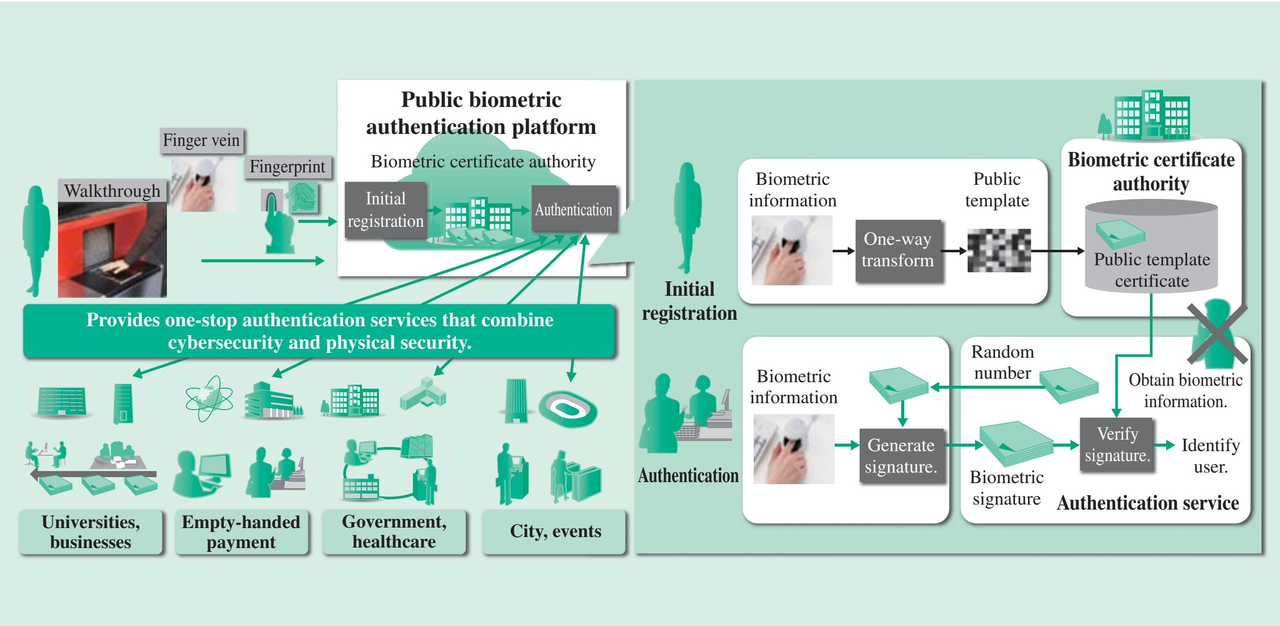

Fig. 2—Overview of Public Biometrics Infrastructure.
The user only needs to register once by providing their public template certificate to the certification authority. Because the same public template certificate can be used by different services, the user is able to access various services without having to repeat the registration process.

they perform authentication, the cost of issuing and managing user-specific smartcards is greater than for the other models.

(2) Perform authentication in a terminal

This involves storing the biometric information in the sensor used as the biometric reader, or in a personal computer or mobile device connected to the sensor. Because it is the responsibility of users to keep their terminals secure, risks include infection by malware due to the difficulty of ensuring that these terminals are always kept safe. If biometric information is stored on terminals like these with poor security, there is a strong risk of it being leaked.

(3) Perform authentication at a data center

This involves storing the biometric information at a data center that is linked to terminals via a network. This is more troublesome for users because each service saves the biometric information in its own data center, meaning users must register for each service separately. Because biometric information for a large number of users is stored in the same place, the damage resulting from any leak is likely to be large.

Accordingly, because existing biometric authentication requires the biometric information obtained from users when they register for services to be stored securely, its problems include the cost of registering biometric information and the risk of it being leaked. The following sections describe a biometric authentication platform that reduces the cost of registering biometric information by overcoming the first challenge of shared use, and a biometric signature technology that reduces the risk of biometric information being leaked by overcoming the second challenge of privacy and security.

Sharable Biometric Authentication Platform

This section describes a sharable biometric authentication platform that can be used by a number of different services. Fig. 2 shows an overview of the PBI.

The PBI provides the platform for incorporating identity authentication into the social infrastructure, including the establishment of new biometric certificate authorities for issuing and managing public template certificates. By making this identity authentication platform available for general use, biometric authentication can be used in applications such as a national ID system, “empty-handed” payment services, password-less authentication in the cloud, and physical security in cities without users having to register separately with each service.

Users confirm their identity with a biometric certificate authority in order to obtain their initial registration. It is envisaged that biometric certificate authorities will include local government in the case of a national ID system, bank branches in the case of payment services, or the information technology

(IT) department of the relevant organization in the case of cloud authentication. When obtaining initial registration, the user's biometric information is supplied to the biometric certificate authority after first being converted into a public template using a one-way transform[*2]. The biometric certificate authority with whom the user is registering affixes a signature to this public template to issue a public template certificate. Because the public template is stored in a form from which the original biometric information cannot be recovered (due to use of the one-way transform), there is no risk of anyone obtaining the biometric information if the template is disclosed. This means that numerous different services can use the same public template.

The following section considers the advantages of using a biometric authentication platform like this. The biometric authentication platform works on a model whereby the biometric certificate authority acts as a repository for certificates that are distributed to services as required, meaning that the information obtained when a user registers can be reused by multiple different services. This overcomes the first challenge of providing a sharable platform.

Digital Signature Technique Using Biometric Information Key (Biometric Signature Technology)

Challenge and response authentication[*3] is one way of preventing the use of replay attacks for spoofing (as described above in the section on the second challenge of privacy and security). While using this method for authentication ensures security, a conventional digital signature requires that a secret key be stored in a smartcard or other device. Accordingly, the problems with this method include the risk of loss or theft of the card and the cost of administration.

Hitachi has developed biometric signature technology that uses biometric information as the secret key, meaning that the secret key is securely stored in the form of the user's own person rather than on a smartcard. The biggest problem with using biometric information as a key is that the data contains a level of error. In the conventional public key infrastructure (PKI), even a single incorrect bit will prevent identity and signature verification. Biometric information, on the other hand, is analog and therefore an allowance for errors is needed. Hitachi developed its biometric signature technology to solve this problem (see Fig. 3).

The biometric signature technology works by extracting a fuzzy key (a stable feature vector with a low level of error) from the biometric information during initial registration and generates the public template from this fuzzy key using a fuzzy signature.

When this public template is subsequently used for authentication, the fuzzy key is extracted from the biometric information in the same way as at initial registration, and then this fuzzy key is used to generate a biometric signature from a random number. The identity of the person can then be confirmed by using their public template to verify their biometric signature.

The following sections describe the steps performed during initial registration and during authentication in more detail.

Initial Registration

First, the fuzzy key extraction algorithm is used to generate the feature vector by extracting features from the biometric information. While biometric information typically contains a large number of errors, feature extraction obtains data with a low level of errors. Next a salt (random number) is added to the feature vector to convert it into the secret key data (fuzzy key) (Step 1).

Next, the key generation algorithm for the fuzzy signature is used to generate the public template, using the fuzzy key as input. Key generation generates a key pair (public key and secret key) (Step 2), and the secret key is embedded in the fuzzy key (Step 3). The key pair generation step is performed using an existing digital signature technique (S) that satisfies the criteria of key homomorphism (such as a Waters signature[*4]). Finally, with the secret key and fuzzy key having been transformed in such a way that they cannot be recovered, an error correction code[*5] is added to create the public template along with the public key (Step 4).

Authentication

First, following the same procedure as initial registration, the fuzzy key extraction algorithm is used to generate the fuzzy key from the user's biometric information (Step 1).

Next, challenge and response authentication is performed using the signature algorithm and verification algorithm from the fuzzy signature method.

*2 A conversion for which there is a mathematical proof that the original information cannot be recovered.

*3 An authentication technique with low vulnerability to replay and similar attacks and that can be implemented using digital signatures based on public key encryption.

*4 The ability to perform operations such as addition and multiplication while still in encrypted form.

*5 Additional data added to enable data errors to be corrected.

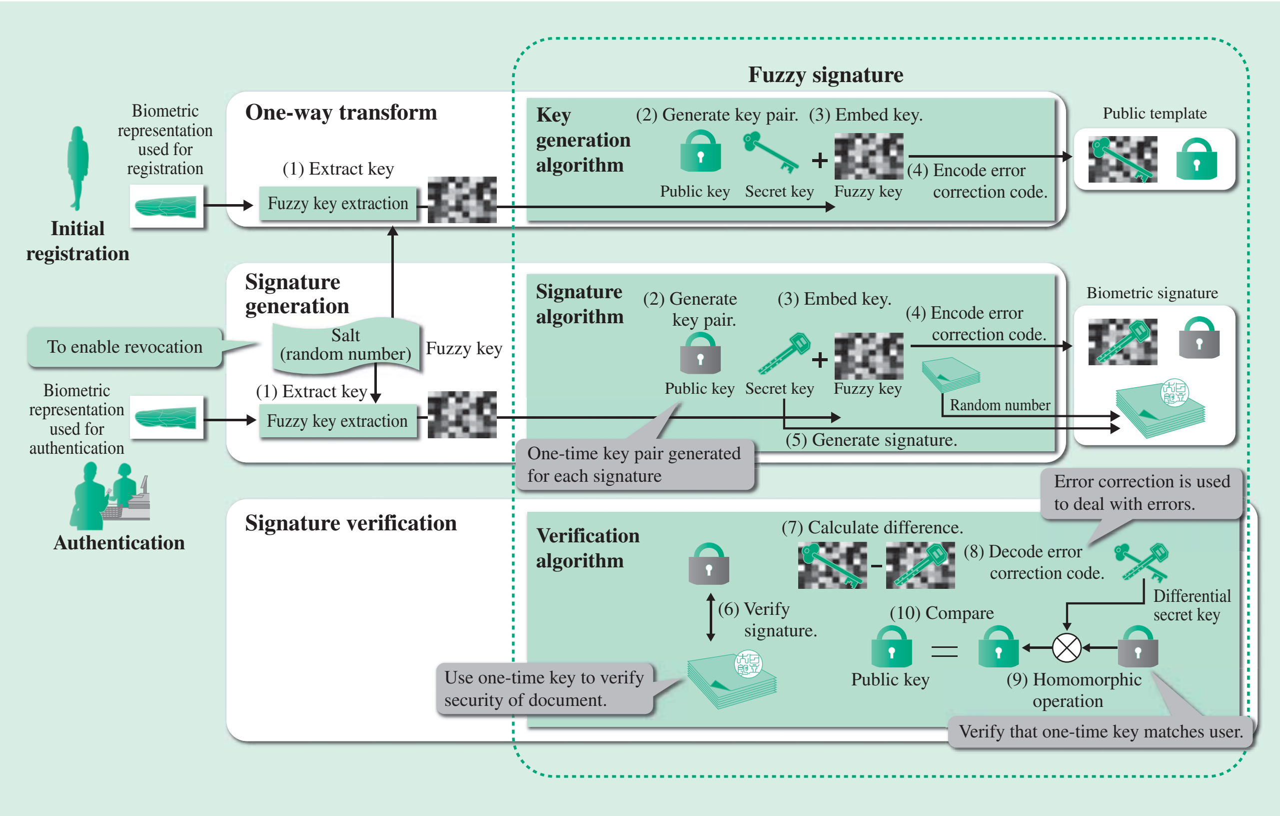

Fig. 3—Overview of Biometric Signature Technology.
To register a user, the fuzzy key is extracted from the biometric representation being used for registration and the key generation algorithm for the fuzzy signature method is used to generate the public template. To perform authentication, the fuzzy key is extracted from the biometric representation being used for authentication and then challenge and response authentication is performed using the signature algorithm and verification algorithm for the fuzzy signature method.

The signature algorithm generates a biometric signature using a random number sent by the server. First, a one-time key pair (secret key and public key) is generated based on the digital signature method (S) (Step 2). Because this one-time key pair is generated at random, the resulting data is different each time. Next, the one-time secret key is embedded in the fuzzy key (Step 3). With this secret key and fuzzy key having been transformed in such a way that they cannot be recovered, an error correction code is added (Step 4). A signature is then generated from a random number using the one-time secret key for the digital signature method (S) (Step 5), resulting in a biometric signature that combines the fuzzy key (which includes the embedded one-time secret key) and the one-time public key.

The verification algorithm checks the validity of the biometric signature. First, the signature generated from the random number is verified using the one-time public key (Step 6). Next, the difference between the fuzzy key that includes the embedded secret key from the public template and the fuzzy key that includes the one-time secret key from the biometric signature is calculated (Step 7). This generates a differential secret key, using error correction to allow for any errors between the biometric information at the time of registration and at the time of authentication (Step 8). The one-time public key is converted by performing a homomorphic operation based on this differential secret key (Step 9), and if the result of this conversion matches the public key in the public template, the biometric signature is deemed to be valid (Step 10).

By using this fuzzy key extraction and fuzzy signature technique, the biometric signature technology is able to be implemented using biometric information as a key.

The security of the biometric signature technology has been demonstrated by a mathematical proof that shows that breaking this method for the purpose of forgery or falsification is sufficiently difficult. Specifically, security has been demonstrated by showing that the unforgeability of the biometric signature is equivalent to that of a Waters signature(4), the unforgeability of which has already been proven mathematically[2]. Accordingly, the second challenge of privacy and security can be overcome by using biometric signature technology as the one-way transform of the biometric authentication platform. By using this biometric signature technology, it is possible to provide signatures and other forms of authentication based on biometric authentication that does not use things like smartcards or passwords, with the same level of security as PKI that is already widely used for things like electronic payments and electronic-government (e-government) services.

BIOMETRIC AUTHENTICATION THAT PROVIDES ACCURATE AND STRESS-FREE PERSONAL IDENTIFICATION

This section describes a biometric authentication technique that can provide accurate and stress-free personal identification, even at venues attended by large numbers of people.

Convenient Biometric Authentication

Hitachi has previously developed a biometric authentication technique that uses the pattern of veins in a person's fingers and deployed it in products for banking, access control and information security. This finger vein authentication technique can achieve a high level of authentication accuracy provided the body part in question is presented in the correct position. Also, finger veins are very difficult to forge because they are an internal characteristic.

A problem, however, is that it is difficult to make authentication quick and simple because it requires the user to stop and present their finger in the correct position. What is needed to combine high authentication accuracy with convenience is a quick and simple operation that can identify people accurately.

Accordingly, Hitachi has developed a biometric authentication technique that is still based on finger vein authentication but can identify people as they walk past, with finger vein authentication that is both accurate and has superior performance in terms of making forgery difficult.

Walkthrough-style Finger Vein Authentication Technology

The finger vein authentication technique uses a finger vein pattern obtained by shining near-infrared light onto the user's fingers and capturing an image of the light after it passes through the interior of the fingers. Hitachi has further enhanced the technique by developing walkthrough-style finger vein authentication technology that can identify people quickly and easily using simple and intuitive operation that consists of having them place their fingers on a reader as they walk past it (see Fig. 4).

Fig. 4—Walkthrough-style Finger Vein Authentication Unit.
The unobstructed access to the interface enables users to place their fingers on the reader and identify themselves as they walk past.

Fig. 5 shows diagrams of the prototype authentication unit. In brief, the proposed method involves first using a ranging sensor [three-dimensional (3D) sensor] to detect the position and orientation of the user's fingers. The light sources are controlled based on this information and the finger vein images acquired.

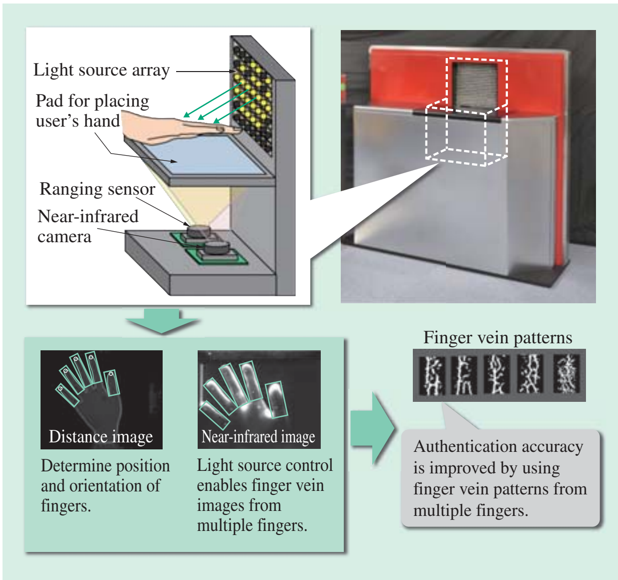

Fig. 5—Authentication Unit Components and Overview of Authentication Process.
A ranging sensor detects the position and orientation of the user's fingers, which are used for adaptive control of the light source array, enabling authentication to be performed using multiple finger vein patterns that are obtained instantaneously.

Finally, the multiple finger vein patterns obtained from these images are compared against existing vein patterns stored in a database to verify identity. The key features of the proposed method are as follows.
(1) Unobstructed interface that does not impede users as they walk past
(2) Control of light sources based on finger position and orientation when capturing finger vein images
(3) Enhanced accuracy through use of multiple finger vein patterns

Firstly, the unit was designed without any obstructions above or on the side where the user is passing to ensure that nothing gets in the way of the user placing their hand on the reader for authentication as they walk past.

To provide flexibility in the position and orientation of the user's fingers on the reader as they walk past and to ensure reliable vein pattern images under these conditions, the system uses an array of multiple light sources. Using a single light source would result in the light not reaching the user's fingers in some cases, depending on where they placed their hand, making it difficult to obtain clear finger vein images. Instead, the control function selects which of the multiple light sources to use based on the position and orientation of the user's fingers to obtain reliable finger vein images regardless of the position and orientation of the user's hand.

To improve authentication accuracy, the system uses multiple fingers. The authentication unit shown in Fig. 4 captures images from multiple fingers simultaneously and provides a larger region for the user to place their hand than previous models that only captured an image from a single finger. This means it achieves greater authentication accuracy by using images of multiple fingers.

Proof of concept testing conducted to demonstrate the throughput and authentication accuracy of the new technique using the prototype unit shown in Fig. 4 was able to identify a maximum of 70 people per minute. Furthermore, although accuracy has only been evaluated for a small sample size, the results indicate that the unit can achieve similar accuracy to current production models even when operating at the above maximum rate of throughput. Because the newly developed walkthrough-style finger vein authentication technology provides a higher level of convenience than previous security techniques, it has potential uses in a wide range of applications. In the future, Hitachi aims to expand its business by using the new technology as a core component of its security solutions.

CONCLUSIONS

This article has described a PBI and walkthrough-style finger vein authentication, two technologies that will be essential to the wider adoption of biometric authentication as a basis for identity authentication in social infrastructure. The use of this technology will make possible a society in which "empty-handed" safety and security can be achieved without the need to use cards or passwords.

In the future, Hitachi intends to proceed with further research and development of biometric authentication and other forms of cybersecurity and physical security to help create a safe and secure society with a high level of convenience.

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Featured Articles

Amorphous Motor with IE5 Efficiency Class

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OVERVIEW: Improving the efficiency of electric motors has become a subject of interest amid growing concern about energy efficiency throughout the world. There have been ongoing improvements in the efficiency of industrial motors prompted by national regulations, with international standards having been formulated to define levels of efficiency. Hitachi has developed axial-gap electric motors that comply with the IE5, the most stringent of these efficiency classes, by utilizing amorphous alloys and drawing on Hitachi's own design and manufacturing technologies. By developing techniques for reducing losses relative to motors in the IE4 efficiency class that involved assessing the motor's internal magnetic characteristics and performing precise analysis and design, Hitachi came up with a motor design that significantly reduces the losses in the amorphous core and succeeded in achieving the IE5 efficiency class.

INTRODUCTION

ELECTRIC motors have long been an essential part of our lives through their use in a wide range of products as a means of converting electrical energy into mechanical energy. Although it is more than 200 years since their principle of operation was first discovered, uses have continued to expand in recent years, including as a source of motive power in vehicles and aircraft, and the development of technologies for improving their performance continues[1]. In the case of industrial motors, efficiency improvement has become a matter of urgency since 2000. Reducing motor power consumption has become a subject of interest against a background of international moves to prevent global warming. Fig. 1 shows a breakdown of power use in Japan[2]. Of total annual power use in Japan of approximately 1 trillion kWh, electric motors account for more than half. In the case of factories and other industrial users, this proportion rises to around 75%. This demonstrates how important it is to improve the efficiency of motors used in industry.

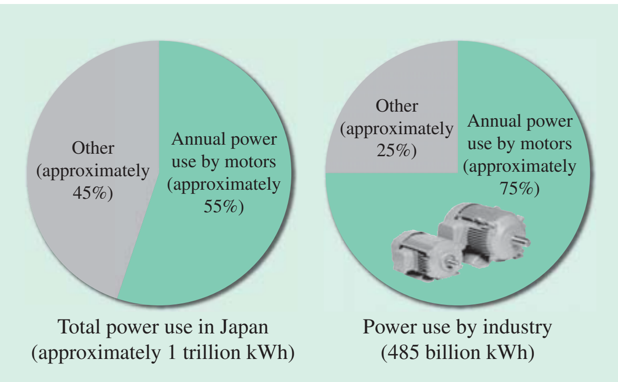


Fig. 1—Power Use in Japan (2009).
As motors account for a large proportion of power consumption in industry, a 1% improvement in motor efficiency in this sector would save the equivalent of the power generated by a major 1-GW power plant.

Countries have responded to this situation by adopting regulations for motor efficiency. The International Electrotechnical Commission (IEC), meanwhile, has defined an international standard for the efficiency of industrial motors, the International Efficiency (IE) code. Internationally, countries have begun introducing requirements that motors satisfy the IE3 efficiency class, with Japan having introduced regulations that stipulate industrial motor efficiency through its Top Runner scheme that came into force from April 2015. This obliges industrial motor vendors to sell motors that achieve an IE3 or better efficiency class.

Following the development in 2008 of the basic technology for an axial-gap motor that achieves superior efficiency through the use of an amorphous alloy core, Hitachi has continued with product developments to increase motor size and further improve efficiency, and to make the technology available in a series of models. A prototype of an 11-kW amorphous motor was successfully completed in 2012 with an efficiency of 93% (high enough to comply with the IE4 efficiency class).

This article describes the development of techniques for further improving efficiency to comply with the more demanding IE5 efficiency class.

IMPROVEMENT IN MOTOR EFFICIENCY FROM USING AMORPHOUS ALLOY

Amorphous alloys are magnetic alloys manufactured by ultra-fast quenching such that the molten metal is solidified at a faster rate than it takes for crystallization to occur (1,000°C in less than 0.001 s, for example). Because of their excellent magnetic properties, amorphous alloys are widely used in applications such as reactors or transformers, and Hitachi has built up know-how in the design and manufacture of such devices. The objective of the current work was to utilize these superior technologies of Hitachi to satisfy the need for energy efficiency in electric motors.

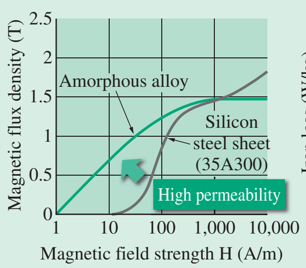
Properties of Amorphous Alloy

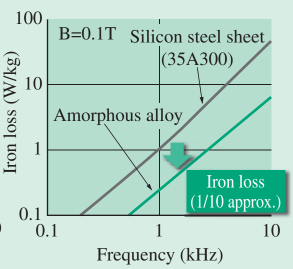
An “amorphous metal” means a metal that does not have a crystalline structure. In this article, the term “amorphous alloy” refers to alloys of iron that exhibit excellent soft magnetic properties that include high permeability and low losses due to their non-crystalline (amorphous) structure (see Fig. 2). Amorphous alloy is recognized as a way of improving the energy efficiency of electrical machinery because its iron loss is only one-tenth that of the silicon steel sheet typically used in motor cores[3].

In 1960, it was discovered that metals could exist in amorphous form, and amorphous alloy intended for use as a soft magnetic material became commercially available from the late 1970s. It has primarily been used as core material for distribution transformers, with a variety of highly efficient models being developed. The volume of amorphous alloy production is currently rising in response to strong demand from markets such as China and India. In contrast, there has been no progress on the use of amorphous alloy in motors despite these being another product that depends on magnetism. This is because the complex shapes of motor cores are difficult to fabricate using thin and hard amorphous alloy.

Techniques for Improving Motor Efficiency

Fig. 3 shows a simplified model that provides a definition of motor efficiency together with a breakdown of the losses that determine this efficiency. The principle by which a motor turns involves passing a current through the coil wound around the core so that the magnetic polarity of the coil flips between north (N) and south (S), thereby inducing a force of attraction or repulsion on the permanent magnet in the rotor. The associated losses include copper losses (Joule losses) due to the current in the coil, iron losses due to the magnetization of the soft magnetic material, and mechanical friction losses. The efficiency of a motor is expressed in terms of the ratio of its output to





Parameter	Silicon steel sheet	Amorphous iron alloy
Material	35A300 (JIS)	2605SA1 (Hitachi Metals)
Photograph	 Rolled sheet	 Ribbon foil
Density	7.7 g/cm^3	7.2 g/cm^3
Thickness	0.35 mm	0.025 mm
B_1 (100 A/m)	0.95 T	1.26 T
Specific resistance	0.52 μΩ•m	1.3 μΩ•m
Losses $W_{10/400}$	18 W/kg	1.5 W/kg
Hardness (HV)	100 to 200	900

JIS: Japanese Industrial Standards

Fig. 2—Properties of Amorphous Iron Alloy.
Although the permeability and iron loss characteristics of amorphous alloy are significantly better than those of the silicon steel sheet typically used in motors, the thin and hard properties of the material have previously prevented it from use in motors.

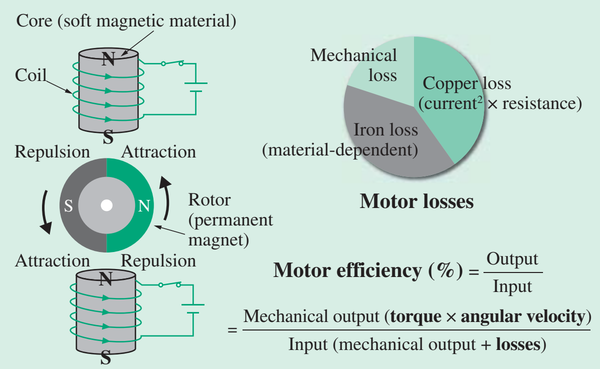


Fig. 3—Principle of Operation of Permanent Magnet Motor, Breakdown of Losses, and Definition of Motor Efficiency.
To improve motor efficiency, it is necessary either to increase mechanical output or reduce losses. Use of amorphous alloy can achieve both these goals.

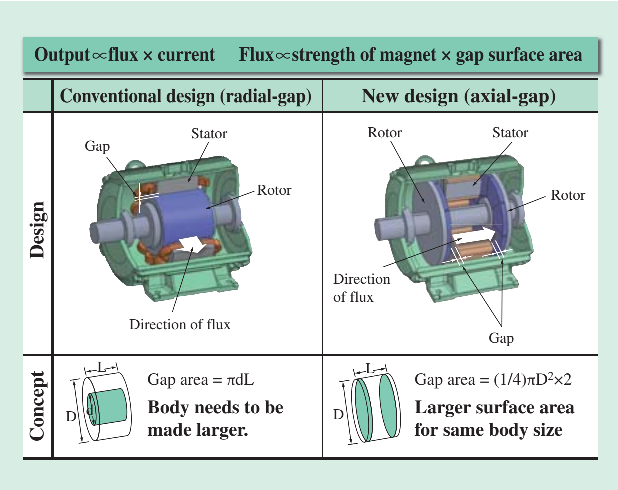


Fig. 4—Comparison of Motor Designs.
Because of its larger rotor diameter, an axial-gap motor has a larger gap area (surface area of the gap region between rotor and stator) relative to volume than a radial-gap motor.

its input. This means that increasing motor efficiency requires either an increase in motor output (torque or speed, etc.) or a reduction in losses.

Because the high permeability of an amorphous alloy means it can generate a high magnetic flux density from a low current, as shown in the graph in Fig. 2, it can increase output torque while also reducing copper losses due to the lower current. Furthermore, because losses are low at high frequency, iron losses can also be kept low even when the motor speed is increased. These features make it an effective way to improve motor efficiency.

Axial-gap Motor Design

Using amorphous alloy for the motor core requires that the core be fabricated without the need for machining it into complex shapes. This led Hitachi to look at using an axial-gap motor with two rotors and to consider a motor design that used amorphous alloy for the stator core. Fig. 4 shows the structural differences between an axial-gap motor and a conventional radial-gap motor. The stator core of an axial-gap motor is a cylinder with a uniform cross-section shape in the axial direction, meaning it is comparatively easy to fabricate using amorphous alloy. Furthermore, a study of the characteristics of axial-gap motors found that they deliver more torque than radial-gap motors when the length in the axial direction is short. This is a result of the rotor diameter being smaller in a radial-gap motor because the rotor is located inside the stator, and also because the rotor is shorter in the axial direction due to the “coil-end” crossover wires of the stator coil that run in the axial direction and therefore take up space in that direction, leaving less area able to contribute to generating torque. The study found that, for typical industrial motors of the same volume, there is an approximately three-fold difference in the torque produced by radial and axial motors (difference in surface area of the gap region between rotor and stator).

Put another way, being able to increase the surface area of the rotor magnet by a factor of around three is equivalent to being able to make the magnetism of the magnet only about one-third as great. The magnets used in motors are expensive because they use large amounts of rare elements, with especially scarce elements such as dysprosium being subject to heightened procurement risk due to reliance on China as a source of supply. Because motors used in industry require security of supply and need to help improve energy efficiency, they need to be made from materials that are low-cost and readily available. Accordingly, Hitachi built an axial-gap motor using very low-cost ferrite magnets with magnetism exactly one-third that of rare earth magnets and conducted performance testing. The results indicated that a motor built with the same volume as existing motors but with an amorphous alloy stator core was able to achieve the IE4 efficiency class (see Fig. 5)[4].

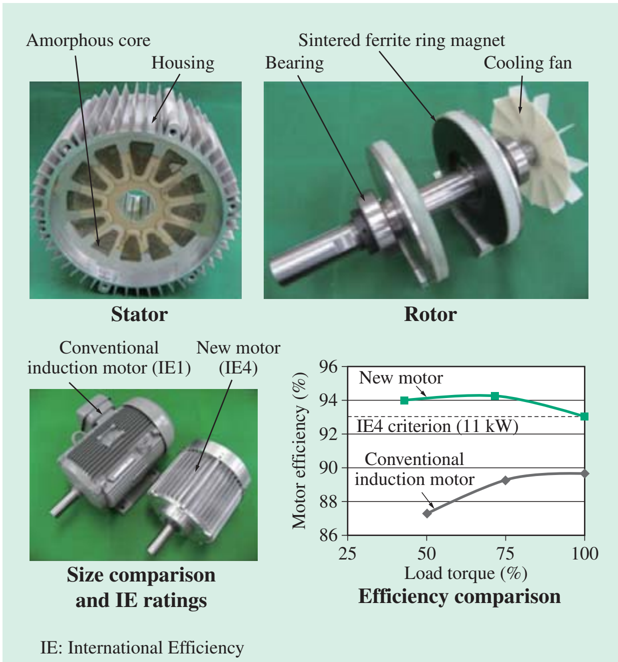


Fig. 5—Design of 11-kW Amorphous Motor, Comparison of Size and Efficiency.
The newly developed motor with an amorphous core and a low-cost ferrite permanent magnet complies with the IE4 efficiency class despite being the same size or smaller than previous models.

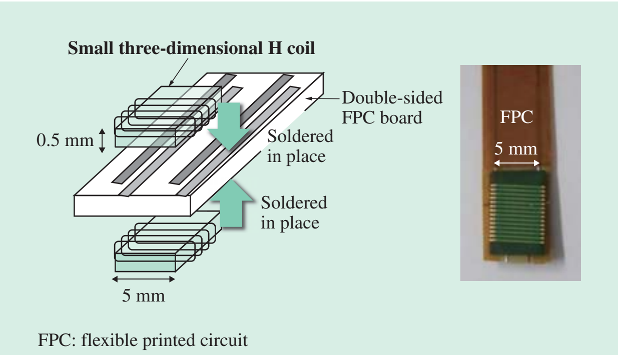


Fig. 6—H Coil Micro-sensor for Measuring Magnetism.
The micro-sensor is able to measure magnetic properties accurately due to improvements in the dimensional and positional accuracy of the two H coils that enable it to be installed in the narrow space next to the magnets.

To achieve an even higher efficiency class, Hitachi then went on to develop techniques for obtaining the best performance from amorphous characteristics. The following section describes these in detail.

LOSS-REDUCTION TECHNIQUES TO ACHIEVE IE5

Technique for Assessing Magnetic Properties of Amorphous Alloy Cores

Achieving the IE5 efficiency class requires a further reduction in motor losses of 20% relative to IE4. Hitachi conducted a study that looked at magnetic properties degradation in amorphous alloy cores as one potential means of reducing losses. While amorphous alloy has exceptionally low-loss characteristics, as shown in Fig. 2, it is known that these characteristics deteriorate in the presence of external disturbances such as applied stress. It was anticipated that the amorphous alloy core used in the new motor would be subject to stress due to the housing design. However, because it had not previously been possible to obtain an accurate determination of the magnetic properties of an amorphous alloy core after it had been fitted in an assembled motor, the design used empirically obtained coefficients to take account of core degradation. This meant that determining the actual degradation would enable an improvement in motor efficiency by allowing the design to use smaller coefficients. Accordingly, Hitachi developed a technique for accurately assessing the magnetic properties of amorphous alloy cores fitted inside assembled motors.

To perform accurate measurement of magnetism, Hitachi developed a very small micro-sensor comprised of two pairs of coils (called "H coils") in precise dimensional alignment. Fig. 6 shows a diagram. It consists of two pairs of very small three-dimensional coils printed in precise alignment on a double-sided substrate and mounted on both sides of a

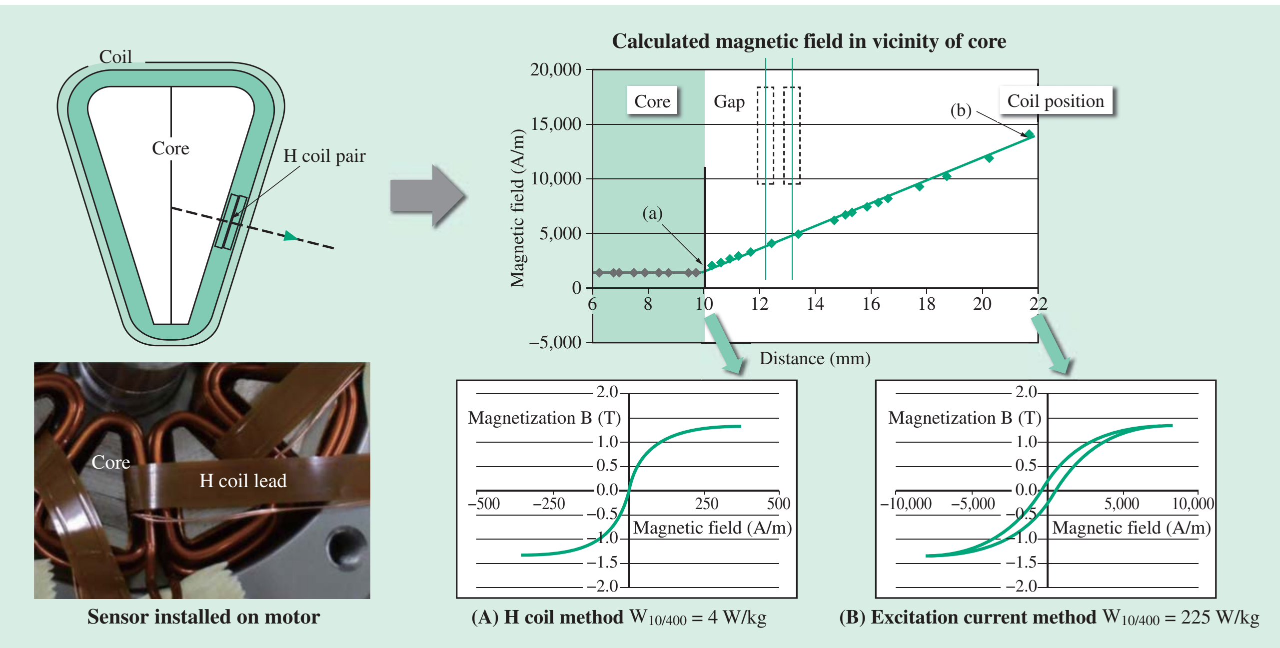


Fig. 7—Overview of Measurement Method for Determining Magnetic Field Applied to Core.
By attaching an H coil on the surface of the motor core (gap between core and coil), it is possible to determine the actual magnetic field applied to the core with high accuracy and obtain the correct magnetic properties.

flexible printed circuit (FPC). Fig. 7 shows an outline of how this micro-sensor was used to make precise measurements of magnetic properties.

Measuring the magnetic properties of a core requires the application of a magnetic field. This applied field is the circumferential magnetic field of the coil (b), and it becomes the weaker field (a) in the vicinity of the core due to the opposing magnetic field of the magnetic core. If the applied magnetic field (b) is strong, a difference appears in the magnetization curve obtained by signal B measured by coil B, as shown by graphs (A) and (B). In (A), both the saturation magnetic field and coercivity are low. The saturation magnetic field is high compared to the magnetic properties of the material and it is subject to mechanical stress. In (B), in contrast, both the saturation magnetic field and coercivity are high. The value of the magnetic field at (b) can be determined easily from the supplied current, in which case the magnetic properties are as shown in (B) and analysis indicates that the core losses make up the bulk of motor losses. On the other hand, if the actual magnetic field applied to the core (a) and the magnetic properties (A) can be determined, the allocation of losses can be adjusted and the accuracy of motor design enhanced.

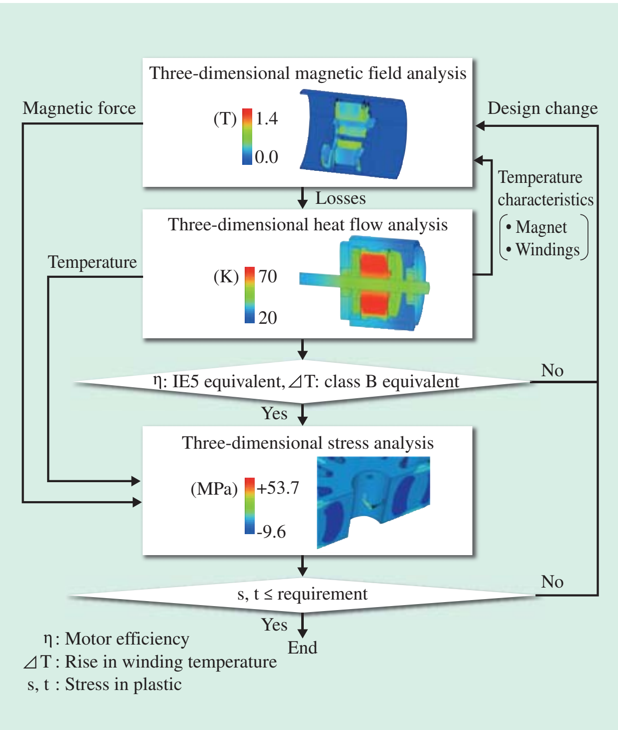


Fig. 8—Flow Chart of Precise Analytical Motor Design.
Parameters such as temperature increase were determined by calculating motor losses with high precision utilizing the losses under actual conditions obtained using three-dimensional magnetic field analysis, and then performing a thermal analysis. The highly accurate prediction of actual conditions allows design margins to be reduced to achieve higher efficiency.

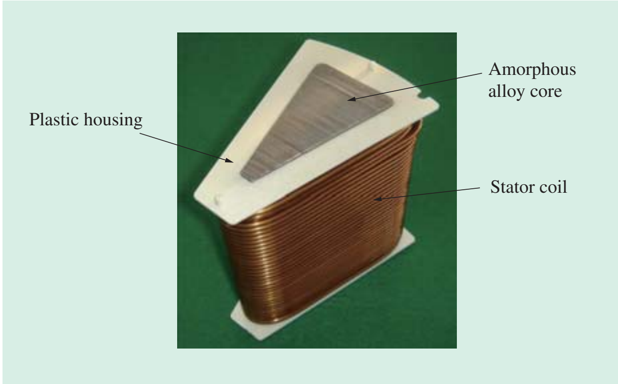


Fig. 9—Design of Amorphous Alloy Core.
The design uses amorphous alloy foil that is first cut and laminated, then inserted into a plastic housing to ensure it holds its shape.

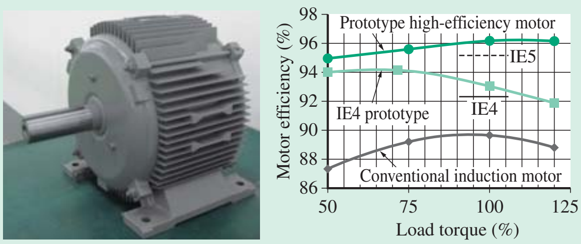
Precise Analytical Design Technique

Fig. 8 shows a flow chart of motor design. To obtain accurate predictions for the three-dimensional magnetic field distribution, temperature distribution, and stress distribution of the axial-gap motor with a double-rotor configuration, the process includes three-dimensional magnetic field analysis, heat flow analysis, and stress analysis. First, the magnetic field analysis is used to calculate the motor losses, output torque, and the magnetic forces on the stator and rotor. Next, heat flow analysis uses these calculated losses as input to calculate the temperature distribution. The magnet and winding temperatures calculated by heat flow analysis are fed back into the physical properties used in magnetic field analysis. From these two analyses, the motor efficiency and temperature rise in the windings are then calculated. If the outcomes satisfy the target performance, the stress analysis is then performed to calculate the stresses on the plastic parts using the electromagnetic force, temperature distribution, and other parameters as inputs. If these stresses are within the permitted limit, the design is complete. The limits are determined based on consideration of how plastic strength varies with temperature and degrades with extended use.

The losses (W_i) in the amorphous core are given by the following equation.

$$W_i = K_h f B^{1.6} + K_e f^2 B^2$$

Here, f is the frequency, B is the maximum magnetic flux density, K_h is the hysteresis loss



Prototype high-efficiency motor **Efficiency comparison**

Fig. 10—Prototype Amorphous Motor with IE5 Efficiency.
Because lower losses mean less increase in temperature, the motor temperature remains within the specification despite not using a cooling fan. The motor also has a much thinner and flatter profile than previous models.

coefficient, and K_e is the eddy current loss coefficient. As the amorphous core losses can be predicted with greater accuracy by using the H coil method for measuring magnetic properties described earlier to determine the actual values of each type of loss in the core, the margins incorporated into the design can be made smaller to produce a design that minimizes motor losses.

AMORPHOUS MOTOR WITH IE5 EFFICIENCY

Low-loss Amorphous Core Design

The IEC is currently considering adding a new efficiency class above IE4. This IE5 class efficiency will stipulate losses 20% lower than IE4. To satisfy this new standard, Hitachi has been utilizing the loss reduction techniques described above to make further efficiency improvements to its amorphous motors. The work has involved investigating the assembly process and looking at core designs that reduce losses based on performance assessments of the amorphous alloy core in an actual motor. This has indicated that the losses in a core that has been fitted in an assembled motor are significantly different depending on the core shape and how it is housed. The use of housings and assembly techniques that do not impose excessive stress on the amorphous alloy can reduce losses by a large margin. Fig. 9 shows the design of the amorphous alloy core. The amorphous alloy foil is cut and laminated and then fitted into a plastic housing that ensures the core keeps its shape. This keeps losses low by insulating the amorphous alloy core from external disturbance such as stress.

Amorphous Motor with IE5 Efficiency

Reducing core losses also has the effect of reducing the amount of heat generated by these losses. Higher efficiency can be achieved through optimal design that takes account of how temperature affects things like electrical resistance and magnet performance. Fig. 10 shows a photograph of the motor with enhanced efficiency. This motor has a flatter profile than the prototype described above that achieved IE4 efficiency, and testing demonstrated that the efficiency improvements have enabled it to remain within the specification for temperature increase even without the presence of a cooling fan. As a result, the motor significantly surpasses the IE5 requirements, thanks in part to the benefits of eliminating the mechanical losses due to the fan[(5)].

Commercial Release of Amorphous Motor

In parallel with achieving world-leading efficiency, Hitachi has also been working on preparing the amorphous motor for commercial release. This includes ensuring safety and reliability, and developing a series of models with a range of capacities and at prices that will be acceptable to customers. Because the new motor has no history of commercial use, being significantly different from previous models in terms both of its design and its manufacturing process, Hitachi performed an extensive variety of prototype tests to confirm it satisfied the required specifications and reliability. The product launch announcement for the IE4 range took place at Japan's largest motor trade show in July 2014 (see Fig. 11)[(6)].

Fig. 12 shows the motor efficiency improvements. An estimate calculated for the replacement of a conventional induction motor with a high-efficiency motor found that, when used to drive a centrifugal pump, an amorphous motor can significantly reduce

Rated output (kW)	3.7 5.5 7.5 11
Speed (min^{-1})	1,500/1,800
Motor efficiency	IE4
Protection	Fully enclosed, external fan (IP44)
Heat-resistant class	Class B
Inverter	WJ200 series

Fig. 11—Commercial Amorphous Motor.
Motors have been released in the high-volume 3.7- to 11-kW capacity range. Models with the same dimensions as IE3 induction motors are available to suit the replacement market.

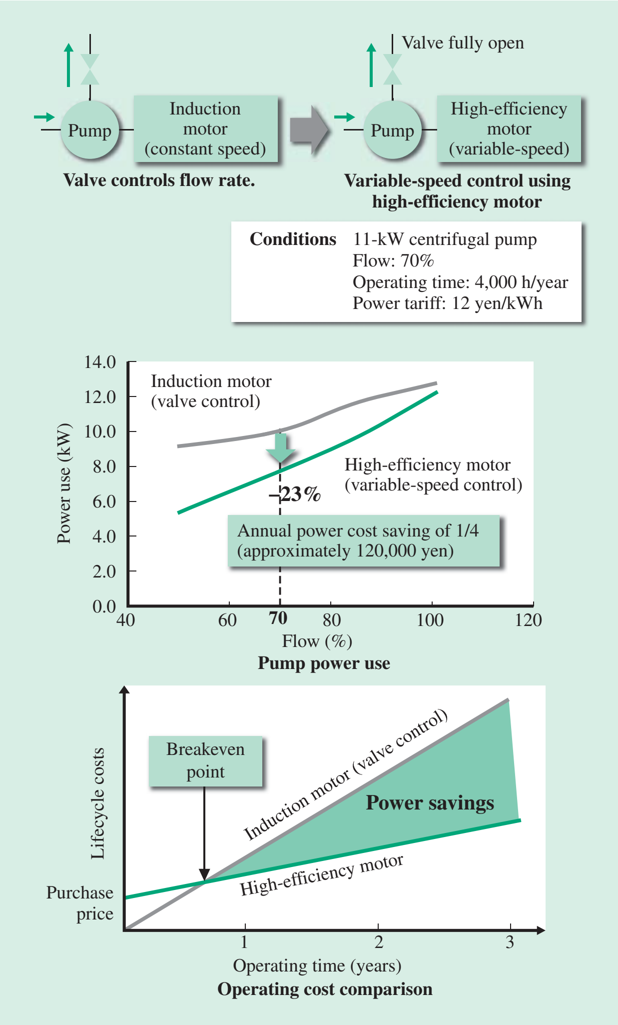


Fig. 12—Benefits of Replacement with High-efficiency Motor.
Use of variable-speed drive and a high-efficiency motor significantly reduced power use. The power savings that result from installation of high-efficiency motors reduce running costs.

power use at times when water is not required. This is in contrast to the difficulty of changing power use when operating an induction motor at constant speed and using a valve to control the water flow. Assuming an annual operating time of 4,000 hours, mean flow rate of 70%, and a power tariff of 12 yen/kWh, this saves approximately one-quarter of power costs compared to the previous motor. Because these power savings outweigh the installation cost of the high-efficiency motor, this clearly demonstrates that the breakeven point can be reached quickly.

CONCLUSIONS

This article has described amorphous motor technology that uses low-loss amorphous alloy to improve the efficiency of industrial motors, which are subject to increasingly stringent efficiency standards.

The cost of the motor is also expected to be low because it uses a ferrite magnet as its permanent magnet. This means that another feature of the motor is that it does not use rare earths, which are subject to supply risks. Hitachi anticipates that the motor will enter wider use as an environmentally conscious product that combines energy efficiency with conservation of precious resources.

The authors also wish to acknowledge that parts of this technology were developed with assistance from the “Rare-Metal Substitute Materials and Usage Reduction Development Project” of the New Energy and Industrial Technology Development Organization (NEDO).

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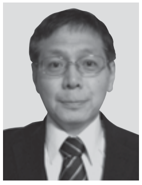

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Featured Articles

Intracardiac VFM Technique Using Diagnostic Ultrasound System

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OVERVIEW: VFM, a technique for imaging blood flow velocity vectors, has been developed to enable the diagnosis of heart disease by using ultrasound to visualize the pattern of blood flow in the heart. VFM is recognized as a non-invasive technique with the potential to provide highly accurate heart disease diagnosis by measuring the velocity vectors, streamline distribution, and vorticity distribution of blood flow inside the heart. The development of the technique included verifying its accuracy to demonstrate its reliability. This accuracy verification consisted of building a heartbeat phantom and comparing the velocities obtained by VFM with those obtained by PIV, a well-established form of laser velocimetry. This demonstrated that VFM is a highly accurate vector imaging technique that is suitable for clinical applications. This article describes clinical applications for valve replacement and dilated cardiomyopathy.

INTRODUCTION

ALONG with magnetic resonance imaging (MRI) and computed tomography (CT), diagnostic ultrasound systems have become a vital diagnostic imaging tool in the healthcare field. The ability to image the interior of the body non-invasively and in realtime using a small and portable instrument has led to a variety of uses for these systems in a diverse range of fields. In cardiovascular medicine in particular, where there is a need to observe the behavior of the fast-moving parts of the heart in realtime, diagnostic ultrasound systems have become an essential diagnostic imaging modality.

The diagnosis of cardiovascular disease requires a way of assessing heart function. The heart can be treated as a pump that undergoes repeated cycles of expansion and contraction to force blood to flow throughout the body, and this pumping function can be assessed by looking at how blood flows through the heart. A variety of methods that use ultrasound and the Doppler effect to measure blood flow behavior have already become vital tools for clinical practice, including color Doppler imaging, continuous wave Doppler imaging, and pulsed wave Doppler imaging.

Fig. 1 shows an echocardiographic image taken using the conventional color Doppler method. Fig. 1 (a) shows the heart being imaged from the ultrasound probe and the relative positions in the echocardiograph, with the image taken such that the left ventricle is on top. The ultrasound beam is emitted from the ultrasound probe in a radial pattern, as shown in Fig. 1 (b), and the velocity of blood flow measured using the ultrasound Doppler effect. By convention, flow toward the probe is shown in red and flow away from probe is shown in blue.

However, the Doppler effect can only be used to determine the component of blood flow velocity in the direction of the beam. It cannot be used to investigate

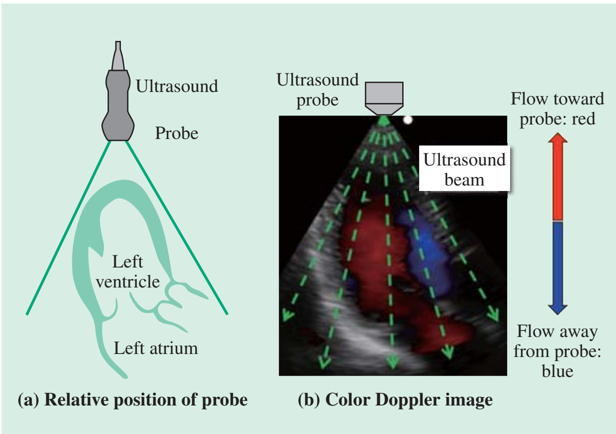


Fig. 1—Echocardiography Images Obtained Using Color Doppler Imaging.
(a) This shows the location of the ultrasound probe relative to heart during cardiography. (b) This shows an example of conventional color Doppler imaging of a heart.

conditions like the direction of flow or presence of vortices. This means there is strong demand from physicians for the imaging of blood flow velocity vectors to provide a more comprehensive picture of blood flow that can be used for detailed diagnosis of heart function.

VFM

To meet this demand, Hitachi has developed the technique of vector flow mapping (VFM), commercializing it in 2013. Fig. 2 (a) shows an example. This technique can provide more intuitive and quantitative imaging of vortex formation, something that is not clearly visible in the color Doppler image in Fig. 1 (b).

As examples of the new functions made possible by VFM, Fig. 2 shows velocity vector, streamline distribution, and vorticity distribution images. The streamline distribution uses lines to indicate the direction of flow and can indicate the trajectory of vortices. The vorticity image uses color to display localized rotational flow and can be used to assess the strength of vortices. Counter-clockwise rotation is defined as positive (red), clockwise rotation as negative (blue), and the color intensity represents the amount of rotation. To develop new heart function diagnostic techniques that use these indices, Hitachi is augmenting its clinical experience with VFM through collaborative research with medical institutions around the world.

VFM TECHNIQUES

Principle of VFM

This section provides a simple explanation of the principle of VFM, which is an improved version[1] of a method proposed by Garcia et al[2]. Fig. 3 (a) shows the coordinate system used in VFM calculations. Because echocardiography involves scanning the ultrasound beam emitted by the probe in a radial pattern, as shown in Fig. 1 (b), it is typically considered in terms of polar coordinates. Using the r coordinate to represent the depth direction and the θ coordinate the angle of the scanned beam, the velocity component in the r direction is v_r and in the θ direction is v_θ.

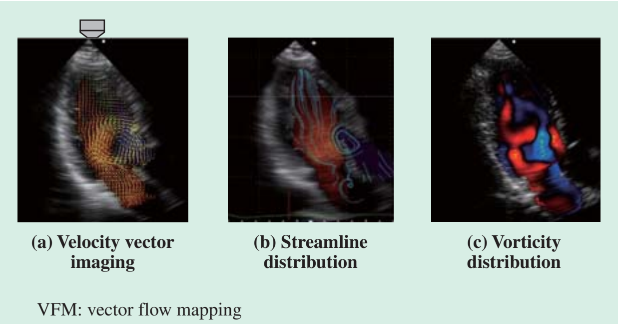


Fig. 2—Functional Overview of VFM.
Three examples of new functions made possible by VFM are: (a) velocity vector imaging, (b) streamline distribution, and (c) vorticity distribution.

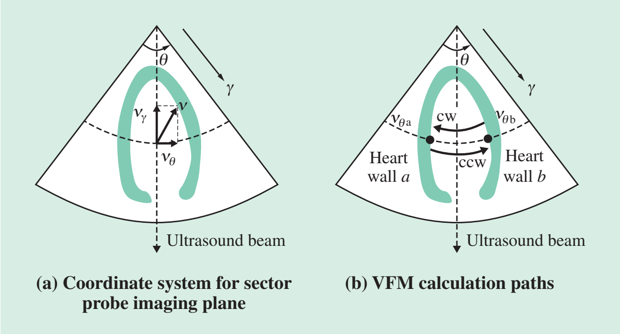


Fig. 3—Overview of VFM Calculation.
The VFM calculation typically uses polar coordinates (a). It is possible to choose either of the two heart walls (a or b) to use as the wall velocity (b).

While the Doppler effect can only measure the v_r component of the three-dimensional blood flow velocity (the component in the direction of the ultrasound beam), VFM uses the conservation of mass to also estimate the velocity perpendicular to the beam direction. Equation (1) expresses the conservation of mass in terms of this polar coordinate system. Here, z is the direction perpendicular to the plane of the image being captured, and v_z is the component of velocity in that direction.

$$\frac{v_r}{r} + \frac{\partial v_r}{\partial r} + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial_z} = 0 \quad (1)$$

Assuming two-dimensional flow (ignoring the influence of the z component), v_θ can be calculated by integrating equation (1).

$$v_\theta = v_{\theta w} + \int \left(-v_r - r\frac{\partial v_r}{\partial r}\right) d\theta \quad (2)$$

Here, $v_{\theta w}$ is the velocity component in the beam direction at the heart wall (boundary between blood flow and wall). It can be calculated by tracking the movement of the wall. As shown in Fig. 3 (b), either of the two heart walls (wall a or wall b) can be chosen for the wall velocity. Using the wall velocity for wall a, equation (2) can be rewritten as follows by integrating in the counter-clockwise (ccw) direction.

$$v_\theta^{ccw} = v_{\theta a}^{T} + \int_a^\theta \left(-v_r - r\frac{\partial v_r}{\partial r}\right) d\theta \quad (3)$$

Here, $v_{\theta a}^{T}$ is the velocity component in the θ direction obtained by heart muscle tracking of point a. Similarly, v_θ^{cw} can be calculated by integrating in the clockwise (cw) direction from wall b. Because, in practice, the velocity components v_θ^{cw} and v_θ^{ccw} in the directions perpendicular to the beam will not match, Garcia et al. used a weighting function to correct for this. Similarly, Hitachi used weighting function correction based on the distance from the wall, as indicated below. Here, θ_a and θ_b are the θ coordinates at the wall boundary.

$$v_\theta (r, \theta) = W v_\theta^{cw} (r, \theta) + (1-W)\, v_\theta^{ccw} (r, \theta)$$

$$W = \frac{\theta - \theta_a}{\theta_b - \theta_a} \quad (4)$$

In this way, the velocity vectors can be obtained from the velocity component in the beam direction measured using the color Doppler method and the velocity component perpendicular to the beam direction obtained from equation (2).

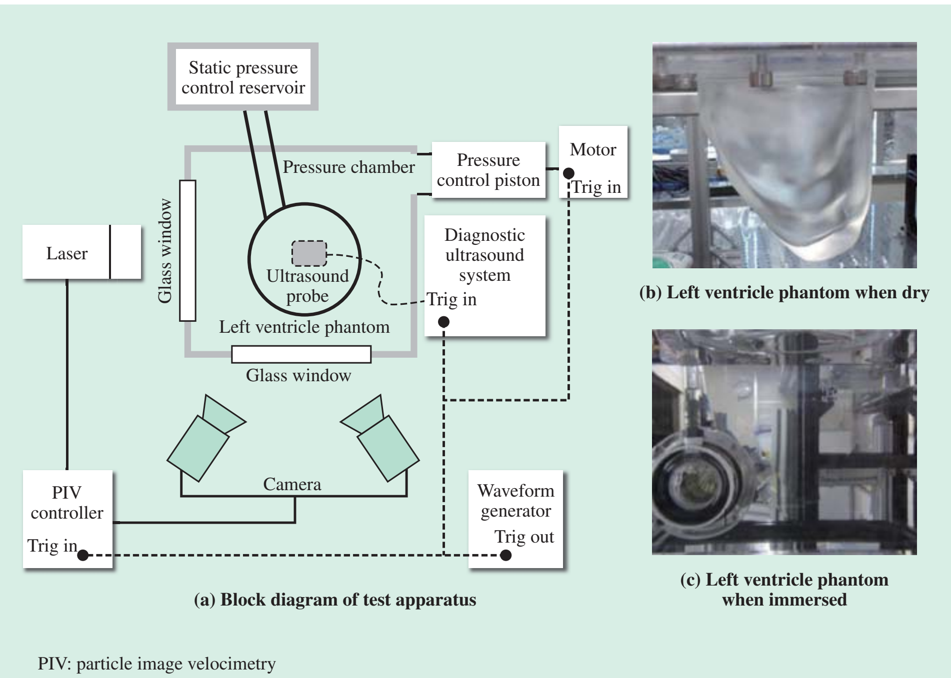
Verification Testing of VFM

While VFM has the advantage of being a simple way to obtain information about blood flow velocity vectors, because the data obtained are estimates based on an assumption of two-dimensional flow, there is a need to adequately validate its accuracy. Hitachi confirmed its reliability by conducting verification testing of VFM accuracy using particle image velocimetry (PIV), the most well-established form of laser velocimetry.

Fig. 4 shows the test apparatus used for this work. It consisted of a left ventricle phantom (a “phantom” is a model of a body part used to test an imaging system), a pressure chamber to drive the beating motion of the phantom, a piston to vary the pressure in the pressure chamber, an ultrasound probe to perform measurements on the left ventricle phantom, and a PIV apparatus to measure the flow inside the phantom. The left ventricle phantom was 1.6 times actual size and was made from transparent modeling urethane resin based on left ventricle anatomical data (model No. 2, Virtual Anatomia*) [see Fig. 4 (b)]. The pressure chamber used to drive the beating motion of the left ventricle was designed to expand and contract the ventricle in step with the change in pressure from the piston.

The pressure chamber shown in Fig. 4 was filled with polyethylene glycol 400 (PEG400) (molecular weight: 400, supplied by Wako Pure Chemical Industries, Ltd.). The measured refractive index of PEG400 is 1.47, which is approximately the same as that of the left ventricle phantom. Selecting a liquid with the same refractive index as the phantom ensured transparency in the pressure chamber, as shown in Fig. 4 (c), and made it possible to use optical methods for measuring flow in the three-dimensional structure of the left ventricle phantom.

* Virtual Anatomia is a trademark of SGI Japan, Ltd.



(a) Block diagram of test apparatus

(b) Left ventricle phantom when dry

(c) Left ventricle phantom when immersed

Fig. 4—Overview of Test Apparatus.
The test apparatus consisted of a transparent left ventricle phantom to enable PIV measurement, a pressure chamber to drive the beating motion of the phantom, a piston to vary the pressure inside the pressure chamber, an ultrasound probe to perform measurements on the left ventricle phantom, and a PIV apparatus to measure the flow inside the phantom.

Mechanical valves equivalent to those used clinically were selected for the mitral valve and aortic valve. The two tubes separated from the top of the phantom by mechanical valves were each connected to a static pressure control reservoir to draw in and expel liquid with the expansion and contraction of the heart.

Fig. 5 shows a comparison of the flows measured by VFM and PIV. Both give the same qualitative results, demonstrating that VFM can represent the actual flow field with good accuracy even when the flow field is three-dimensional. Although VFM is calculated based on an assumption of two-dimensional flow, thanks to the use of error correction [see equation (4)], the flow field it provides is not two-dimensional and is a close approximation of the actual flow field.

A quantitative assessment of VFM and PIV found that the differences between the two methods were approximately 10% of the color Doppler velocity range being measured. Based on this result, work has now proceeded to clinical testing.

CLINICAL USE

Post-operative Artificial Valve Replacement Case

In post-operative artificial valve replacement cases, the pattern of blood flow is sometimes abnormal even if the pumping function of the heart is normal. In a case in which the mitral valve was replaced by a mechanical valve, the flow of blood into the left ventricle in the diastolic (expansion) phase was directed toward the ventricular septum forming a counter-clockwise vortex [see Fig. 6 (a)]. With the passage of time, this vortex shrunk and slowed, while a new vortex formed in the ventricular apex [see Fig. 6 (b)]. The direction of rotation of this vortex can be seen in the vorticity image [see Fig. 6 (c)]. In the vorticity image, red indicates the vortex is rotating counter-clockwise and blue indicates clockwise rotation (data courtesy of Tokuhisa Uejima of the Department of Cardiovascular Medicine, The Cardiovascular Institute).

Dilated Cardiomyopathy Case

In a dilated cardiomyopathy case, the left ventricle was dilated compared to a healthy organ, with a large vortex forming from the center of the left ventricle toward the ventricular apex during the diastolic phase, as shown in Fig. 7. It was found that this vortex remained present and prevented blood from flowing efficiently during the systolic phase. This demonstrates the close links between heart disease and how blood

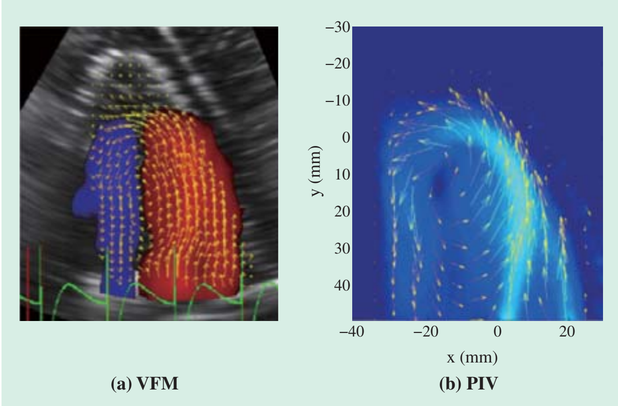


Fig. 5—Comparison of Blood Flow Patterns Obtained Using VFM and PIV.
The flow fields obtained using VFM and PIV are qualitatively the same, demonstrating that VFM can represent the actual flow field with good accuracy even when the flow field is three-dimensional.

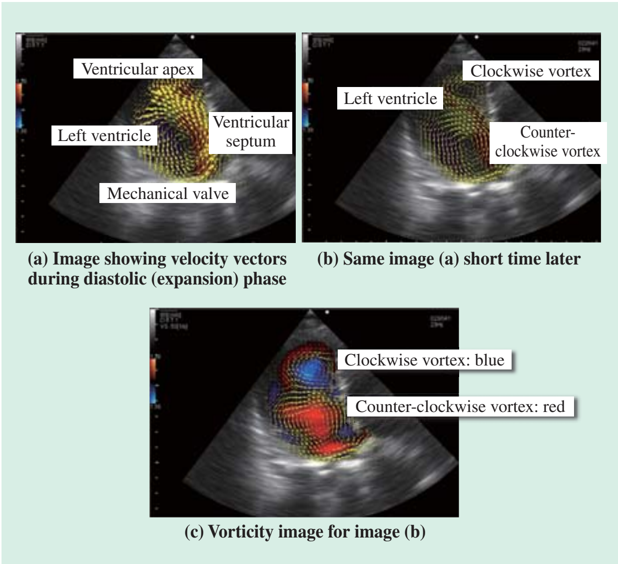


Fig. 6—Blood Flow in Left Ventricle with Artificial Valve.
The direction of rotation of vortices could be determined in a post-operative artificial valve replacement case.

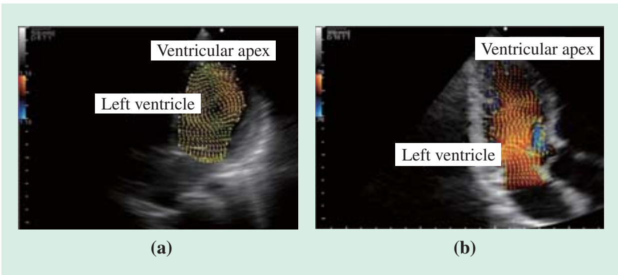


Fig. 7—Dilated Cardiomyopathy Case.
When a case of dilated cardiomyopathy (a) is compared to a healthy organ (b), the left ventricle is dilated and a large vortex forms from the center of the left ventricle toward the ventricular apex during the diastolic phase, and persists at the same location.

flows (data courtesy of Keiichi Itatani, Department of Cardiovascular Surgery, Kyoto Prefectural University of Medicine).

CONCLUSIONS

VFM was developed to enable the detailed study of blood flow in the heart. While it is sometimes difficult in medicine to obtain the actual value of the quantity being measured, resulting in a lack of adequate accuracy verification, the accuracy of VFM was demonstrated using laser measurements.

While this article has presented examples of the utility of VFM for artificial valve replacements and dilated cardiomyopathy, clinical data is also being collected for other cases. Hitachi hopes to continue contributing to medical progress in the future by demonstrating how VFM offers even greater clinical value.

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Featured Articles

Analysis Technique for Improving Coercivity of Nd-Fe-B Magnets and Development of Dy-free Magnet

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OVERVIEW: Hitachi is working to improve the performance of the Nd-Fe-B magnets that help make people's way of life more energy efficient and reduce the load it places on the environment. To study the factors that govern coercivity, an important parameter of magnet performance, Hitachi used a combination of advanced measurement techniques for evaluating the magnetic properties of a magnet's internal structure and simulation techniques for analyzing magnetization reversal behavior. This analysis found that the properties of the grain boundary phase have a strong influence on coercivity. By working on material developments that focused on the grain boundary phase, Hitachi Metals, Ltd. has commercialized the NEOMAX Low Dy Series, a new range of Nd-Fe-B magnets developed to significantly reduce the use of Dy, a rare element.*

INTRODUCTION

SINTERED magnets made from neodymium (Nd), iron (Fe), and boron (B) (hereinafter referred to as Nd-Fe-B magnets) are the most powerful permanent magnets currently available. They are used in information technology (IT) equipment, home appliances, electric vehicles (EVs), and a wide range of products such as industrial electric motors that underpin social infrastructure[1] (see Fig. 1). Demand has been rising in recent years amid moves to make people's way of life more energy efficient and reduce the load it places on the environment, particularly for the Nd-Fe-B magnets used in the drive motors in hybrid electric vehicles (HEVs) and EVs.

Coercivity is an indicator of a magnet's stability in the presence of a magnetic field. A key challenge for the magnets used in HEVs and EVs is to improve this coercivity without compromising high remanent magnetic flux density that generates the strong magnetic force. While the addition of dysprosium (Dy), a rare element, is one way of improving coercivity, Dy poses a significant procurement risk in terms of its security of supply and price fluctuations. This has created an urgent need to develop ways of achieving high coercivity while also reducing the quantity of Dy in the magnet.

The Research & Development Group at Hitachi, Ltd. is working on the research and development of high-performance Nd-Fe-B magnets in collaboration with Hitachi Metals, Ltd., which is responsible for the magnet business. If magnets are to be developed with high coercivity but without relying on Dy, it is particularly important to identify the factors that determine coercivity. This article describes analysis techniques for magnets that combine measurement

Nd: neodymium   Fe: iron   B: boron

Fig. 1—Nd-Fe-B Magnet Product Range[1].
Hitachi supplies Nd-Fe-B sintered magnets in a variety of shapes and sizes to suit different applications.

* NEOMAX is a trademark of Hitachi Metals, Ltd.

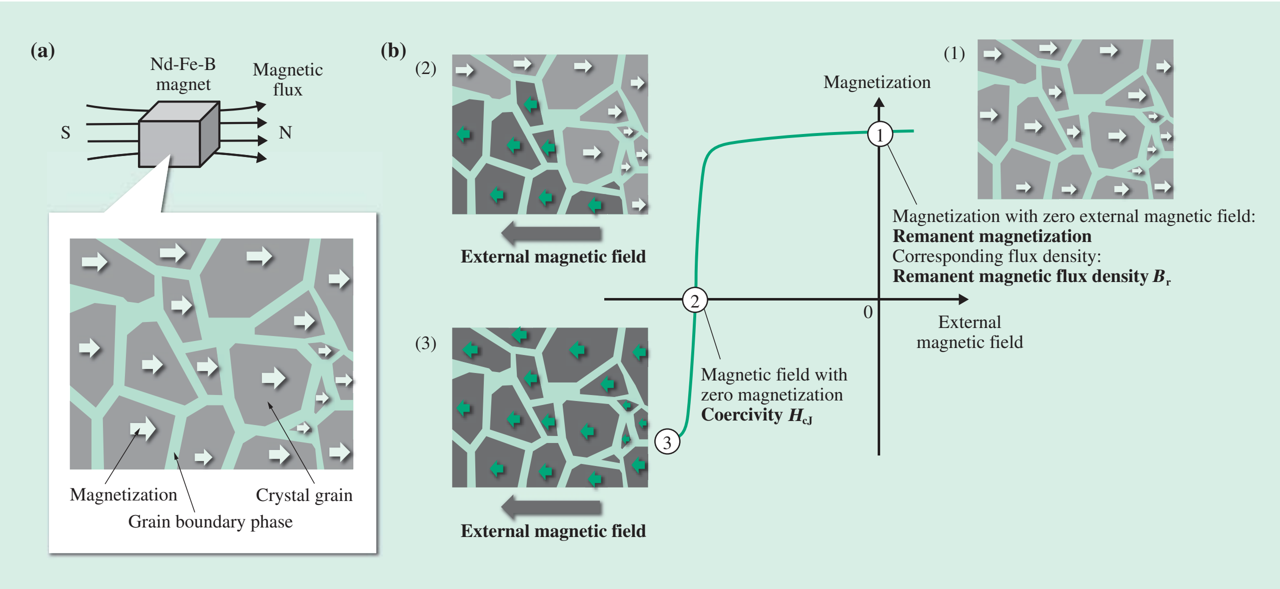

Fig. 2—Schematic Diagrams of Microstructure and Magnetic Properties of Nd-Fe-B Magnets.
(a) The magnet is made of micrometer-sized crystal grains, each of which has magnetization. (b) The magnetization of the grains can be flipped by the application of an external magnetic field, and this polarity reversal occurs if the magnetic field exceeds the material's coercivity.

and simulation to elucidate the mechanisms involved in coercivity, and the new Dy-free Nd-Fe-B magnets developed by Hitachi Metals.

STRUCTURE AND MAGNETIC PROPERTIES OF ND-FE-B MAGNETS

The properties of a magnet, including the remanent magnetic flux density and coercivity described above, are closely related to the magnet's internal microstructure. Fig. 2 shows schematic diagrams of the microstructure and magnetic properties of Nd-Fe-B magnets. Nd-Fe-B magnets have a multi-grain structure made up of Nd-Fe-B crystal grains separated from each other by a grain boundary phase with a thickness of several nanometers. These grains have individual magnetization, and they as a whole generate a unidirectional magnetic flux. Fig. 2 (b) shows how the magnetization changes when an external magnetic field is applied to a magnet. The density of magnetic flux when there is no external magnetic field present is called the remanent magnetic flux density (B_r), [diagram (1) in Fig. 2 (b)], which is equivalent to the strength of magnetization present at that time (remanent magnetization). When an external magnetic field is applied, the magnetic orientations of some of the grains in the magnet reverse [indicated by the transition from diagram (1) to (2) in Fig. 2 (b)], and this continues until all grains have switched their magnetization directions [diagram (3) in Fig. 2 (b)]. The coercivity (H_{cJ}) is the absolute value of the external magnetic field that causes half of the grains in the magnet to reverse their magnetization, resulting in net magnetization of zero [diagram (2) in Fig. 2 (b)]. In other words, coercivity is an indicator of how well the magnet can withstand magnetization reversal due to an external magnetic field, with HEV and EV applications in particular requiring high coercivity.

Coercivity is dependent on a number of factors in the magnet's microstructure, and the mechanisms by which it manifests are not yet well understood. To elucidate the factors that determine coercivity, it is necessary to understand both how magnetization reversal occurs in single grains and how it propagates across grain boundaries. The following sections describe the results of this study.

MEASUREMENT OF MAGNETIZATION REVERSAL IN SINGLE GRAINS

The theoretical coercivity of a magnetic grain can be determined by assuming uniform magnetization rotation throughout the grain, which corresponds to the anisotropy field for the material (5.7 MA/m in the case of Nd-Fe-B). However, the actual coercivity of Nd-Fe-B magnets is only between 20 and 30% of this value. Furthermore, the grains are much larger than would be needed to satisfy the theoretical assumption of uniform rotation taking place simultaneously throughout the grain. That is, rather than magnetization reversal in magnet grains happening all at once, it was assumed that each grain contained a number of magnetic domains (regions of uniform magnetic orientation) and that the mechanism for the reversal of the entire grain involved the movement of the boundaries between these (the domain walls). However, no direct observations had been made to confirm this.

Accordingly, this research included an experiment that directly observed magnetization reversal of single-crystalline grains. An X-ray magnetic microscope was used to perform measurements on microscopic grains of similar size to the crystal grains in magnets. Fig. 3 shows the experimental method. First, particles of single-crystalline Nd-Fe-B were prepared with a similar size to the grains in magnets (6 μm in diameter, 6 μm high) and attached to the tip of a tungsten (W) shaft, over which a W cap was formed, as shown in Fig. 3 (a). These Nd-Fe-B particles were obtained from a single-crystalline sample using a microsampling technique based on focused ion beam fabrication. The sample was measured using an X-ray magnetic microscope installed in the BL16XU industrial consortium beamline at the SPring-8 synchrotron radiation facility. This performed measurements based on the X-ray magnetic circular dichroism (XMCD) principle. When circularly polarized X-rays are directed at a magnetic material, the interaction between the X-rays and magnetism causes the amount of X-ray absorption to be different depending on the polarization (left- or right-handed). This difference in absorption (XMCD intensity) depends on the angle of the incident X-rays relative to the magnetization of the material. Measuring the XMCD intensity while sweeping the external magnetic field, as shown in Fig. 3 (b), can determine the change in magnetization due to the external magnetic field and obtain the magnetization curve shown in Fig. 2 (b). Furthermore, by rotating the sample to change the relative orientation of the magnetization and the external magnetic field,

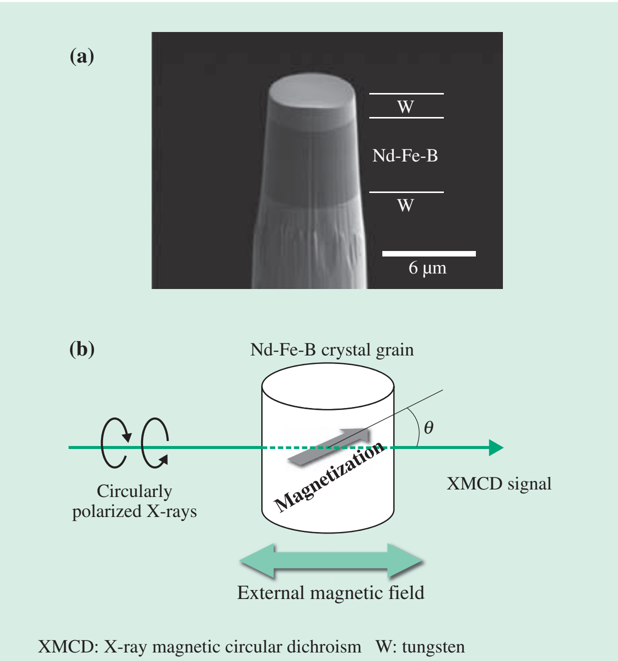

Fig. 3—Method for Measuring Magnetization Reversal in Microscopic Nd-Fe-B Crystal Grains.
Fig. (a) shows an electron microscope image of sample. Fig. (b) shows how the magnetization of the sample can be determined from the XMCD signal obtained through the interaction between the magnetization of the Nd-Fe-B crystal grain and the incident circularly polarized X-rays.

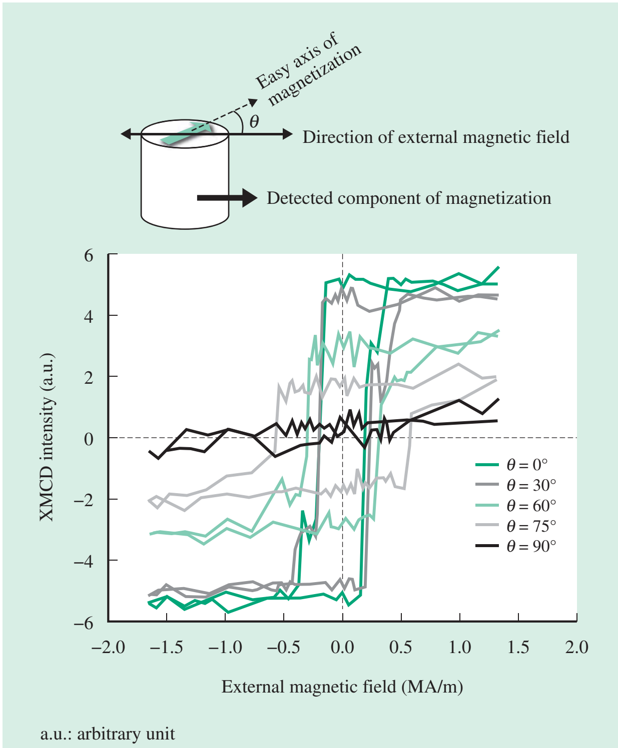

Fig. 4—Dependence of Magnetization Curve of Microscopic Nd-Fe-B Crystal Grains on Angle of Applied Magnetic Field.
The XMCD intensity (vertical axis) indicates the degree of magnetization. The magnetization curve is measured by varying the angle (θ) of the applied magnetic field relative to the easy axis of magnetization. The detected component of magnetization falls as θ becomes larger, representing higher coercivity, which indicates that the mechanism of magnetization reversal in crystal grains involves domain wall motion rather than occurring all at once.

it is possible to measure the dependence of the magnetization curve on the angle of the applied magnetic field, and thereby to determine the nature of the magnetization reversal mechanism.

Fig. 4 shows the results of the experiment in terms of the change in the magnetization curve due to changing the angle of the applied magnetic field. As the angle between the external magnetic field and the magnetization becomes larger, the switching field (coercivity) increases and the XMCD intensity (remanent magnetization) for zero external magnetic field becomes weaker. This indicates that rather than the magnetization reversal of Nd-Fe-B crystal grains occurring all at once, it occurs through the typical domain wall motion mechanism. Furthermore, the way in which magnetic domains form during magnetization reversal is indicated by the magnetization maps obtained from the magnetization curve and XMCD signal, which are shown in Fig. 5. The maps are color-coded to show the direction of magnetization. The figures show how, starting from an initial state in which all of the magnetizations are in the positive direction [Fig. 5 (c)], the distribution of internal magnetizations gradually changes as the applied magnetic field is increased, with reversal occurring progressively rather than all at once [as shown in Fig. 5 (d), (e), and (f)]. These direct measurements indicate that the mechanism for magnetization reversal in the Nd-Fe-B crystal grains of magnets involves domain wall motion rather than simultaneous reversal.

GRAIN BOUNDARY PHASE CHARACTERISTICS AND RELATIONSHIP WITH MAGNETIZATION REVERSAL

Evaluation of Grain Boundary Phase Magnetization

The process of magnetization reversal across the entire magnet involves not only the reversals within individual crystal grains but also their propagation from grain to grain. It is anticipated that the grain boundary phase will exert a strong influence on this process. The magnetism of this phase has been a subject of interest because recent research has suggested the possibility that the grain boundary phase contains high concentration Fe and is ferromagnetic[(2)]. This research

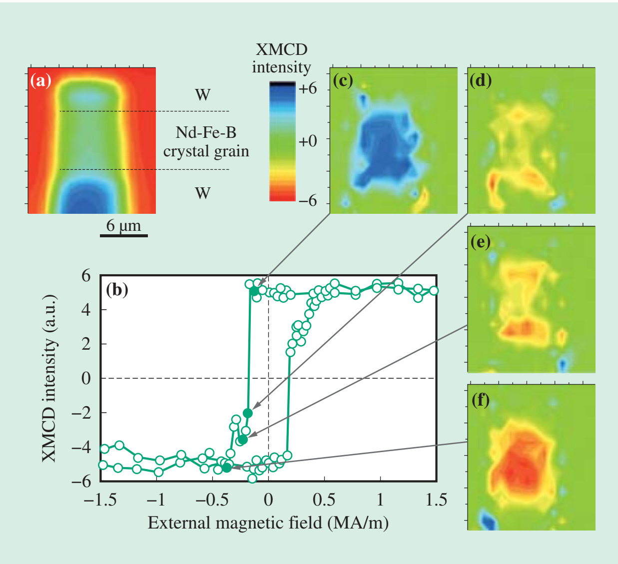

Fig. 5—Magnetization Map during Magnetization Reversal in Microscopic Nd-Fe-B Crystal Grain.
Mapping magnetization shows the process of magnetization reversal when an external magnetic field is applied to a Nd-Fe-B crystal grain. Image (a) is color-coded to show the differences in material-dependent X-ray absorption. The magnetization curve in graph (b) and the magnetization maps in (c), (d), (e), and (f) show that the change in magnetization during reversal does not occur all at once, but rather progressively through the crystal grain.

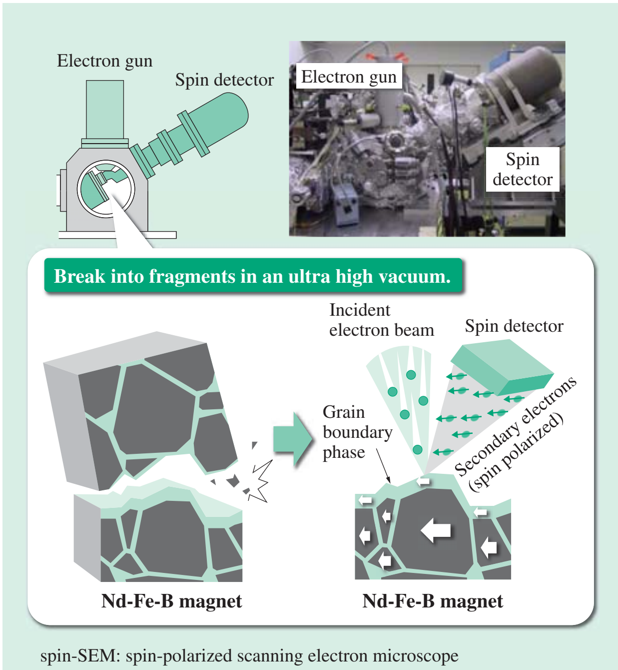

Fig. 6—Magnetization Measurement of Grain Boundary Phase Using Spin-SEM.
The figures show how the spin-SEM is used to perform measurements. Breaking up a magnet in an ultra high vacuum leaves the grain boundary phase exposed on the surface of the fragments. The magnetization of this grain boundary phase can then be determined from the spin polarization of secondary electrons generated by directing an electron beam at the grain boundary phase.

involved using a spin-polarized scanning electron microscope (spin-SEM), a type of electron microscope specifically developed by Hitachi for measuring magnetization, to make direct measurements of the magnetism of the grain boundary phase(3). Fig. 6 shows how a spin-SEM is used to make measurements. First, a sample Nd-Fe-B magnet is mechanically fractured inside a chamber held in a state of ultra high vacuum. As most fracturing occurs preferentially along grain boundaries, this causes the grain boundary phase to be exposed on the surface of the resulting fragments, as shown in the figure. When an electron beam is directed at such surfaces, secondary electrons generated inside the grain boundary phase carry information about the magnetization of this material (spin polarization). Accordingly, quantitative measurements can be made of the magnetization of the grain boundary phase by detecting these electrons in a spin detector.

Fig. 7 shows the results of measuring the grain boundary phase magnetization for an Nd-Fe-B magnet using a spin-SEM. A series of magnetization measurements were performed accompanied by milling of the fractured surfaces using argon (Ar) ions. As indicated by the measurement results in the figure, the spin-SEM image taken immediately after fracture (0 nm of milling) shows a clear black and white pattern of magnetic domains in those places where the Nd-Fe-B crystal grain (Nd-Fe-B phase) is exposed, whereas the image for the region marked as being a grain boundary phase has poor contrast. As the amount of milling is increased, however, the contrast between black and white gradually sharpens in the grain boundary phase region. This is because the grain boundary phase coating the surface is progressively milled away, eventually leaving the underlying Nd-Fe-B phase exposed. The graph at the bottom of Fig. 7 shows a plot of this change in terms of the magnetization of the grain boundary phase region (the region initially coated with the grain boundary phase immediately after fracturing). The magnetization immediately after fracturing and during initial milling (milling of 0 to 1 nm) remains constant, this being the magnetization of the grain boundary phase. The results indicate this magnetization is 37% that of Nd-Fe-B phase. The results thereby demonstrate that the grain boundary phase in typical Nd-Fe-B magnets is ferromagnetic. This ferromagnetic grain boundary phase strengthens the magnetic coupling between Nd-Fe-B crystal grains and is a cause of lower coercivity because it encourages the propagation of magnetization reversal between crystal grains.

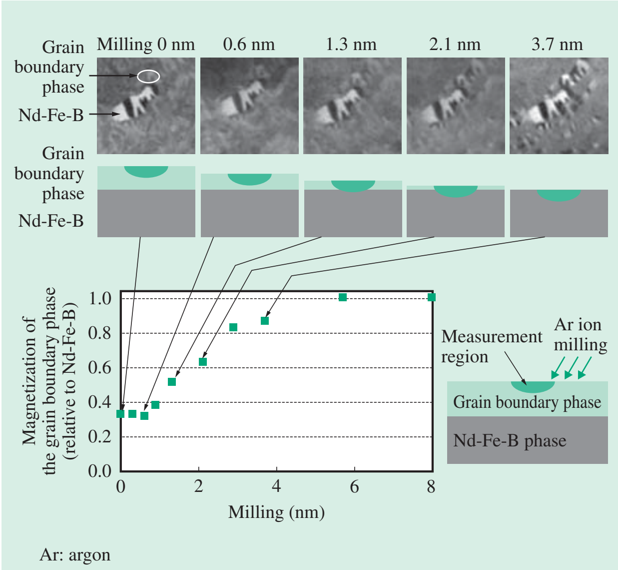

Fig. 7—Results of Magnetization Measurement of Grain Boundary Phase Using Spin-SEM.
The magnitude of detected magnetization changes as progressive milling of the grain boundary phase exposed on the fractured surfaces gradually uncovers the underlying Nd-Fe-B phase, in which the magnetic domains appear sharply contrasted. The measurements made initially and in the early stages of milling represent the magnetization of the grain boundary phase, which is 37% that of Nd-Fe-B phase.

Simulation Analysis of Magnetization Reversal

The simulation of magnetization reversal provides an effective way of systematically studying how it is influenced by the properties of the grain boundary phase. The research team has developed an analytical simulation technique based on micromagnetics theory that provides tools for analyzing the dynamics of magnetization. This technique is called Landau–Lifshitz–Gilbert (LLG) simulation because it uses the LLG equation to calculate how magnetization behaves in a magnetic field. Hitachi used this to calculate and compare the differences in magnetic reversal that result from changing the properties of the grain boundary phase.

First, a two-grain model was formulated consisting of two Nd-Fe-B crystal grains separated by a grain boundary phase. This was then used to study how the strength of magnetic coupling between the grains varied in response to changes in the thickness of the grain boundary phase and its magnetization. As shown in Fig. 8 (a), the strengths of magnetic coupling between the grains via the grain boundary phase were calculated for the planes perpendicular to and parallel to the direction of crystal grain magnetization (series coupling and parallel coupling, respectively). The calculation results are shown in Fig. 8 (b) and (c). As shown in Fig. 8 (b), the magnetic coupling between grains was dependent on the grain boundary phase thickness, becoming stronger as the grain boundary phase becomes thinner. The magnetic coupling between grains also tends to become stronger as the magnetization of the grain boundary phase increases, as shown by Fig. 8 (c). The stronger this magnetic coupling between grains, the easier it is for the magnetization reversal of one grain to propagate to the other. In other words, it encourages magnetization reversal across the entire magnet and therefore implies that coercivity will be reduced.

To test this, Hitachi prepared a three-dimensional model with multiple grains to investigate how the properties of the grain boundary phase influenced the propagation of magnetization reversal. Fig. 9 shows the results of calculating how magnetization reversal occurs for a model of four crystal grains under two different grain boundary phase conditions with different levels of magnetization. The grain boundary phase for case A is non-magnetic (no magnetization) and for case B is ferromagnetic with magnetization of 0.65 T (40% of Nd-Fe-B phase). In both cases, the grain boundary phase is 3 nm thick. The figures are color-coded to show the direction of magnetization, with red indicating right-handed and blue indicating left-handed magnetization. Although not shown in the figure, rather than being in a vacuum, the model treats the four grains as being surrounded by magnet grains. That is, the model simulates the situation in the interior of a magnet. As shown in Fig. 9, when the external magnetic field is low (–2.5 MA/m), the magnetization across the entire region is uniformly right-handed. As the field strength is then increased, magnetization reversal starts to occur at some locations inside the grains, indicated by the increase in blue regions (left-

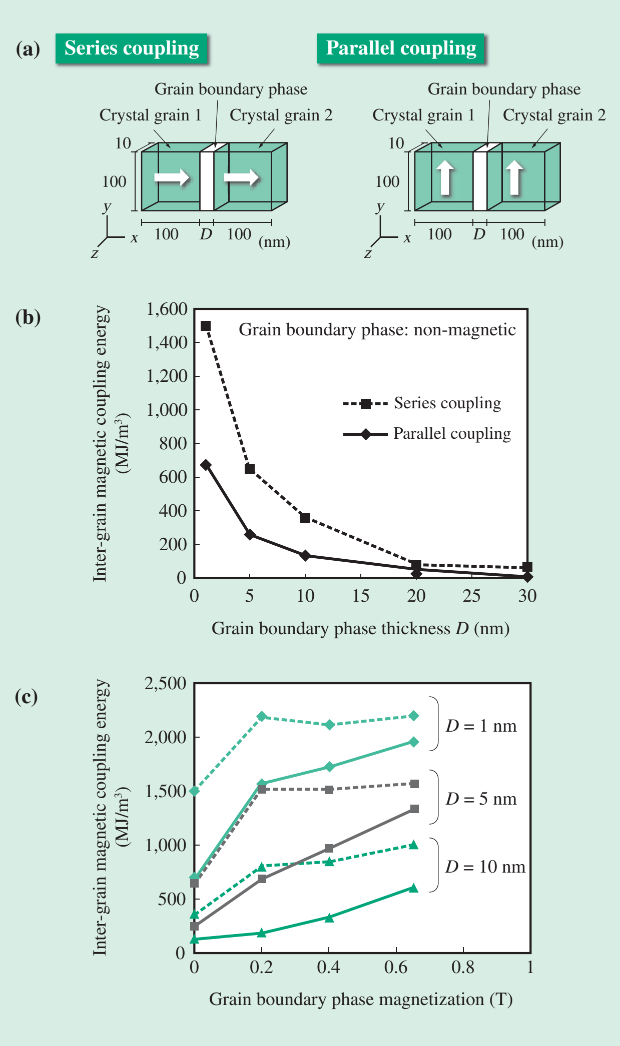

Fig. 8—Results of Calculating Magnetic Coupling across Grain Boundary Phase Using Two-grain Model.
Fig. (a) shows the model used to calculate the magnetic coupling across a grain boundary phase for planes perpendicular to and parallel to the direction of magnetization (series coupling and parallel coupling respectively). Graphs (b) and (c) respectively show how the strength of magnetic coupling between the grains increases when the grain boundary phase is thin and when it has high magnetization. The dotted lines in the graphs represent the calculated values for series coupling and the solid lines are for parallel coupling.

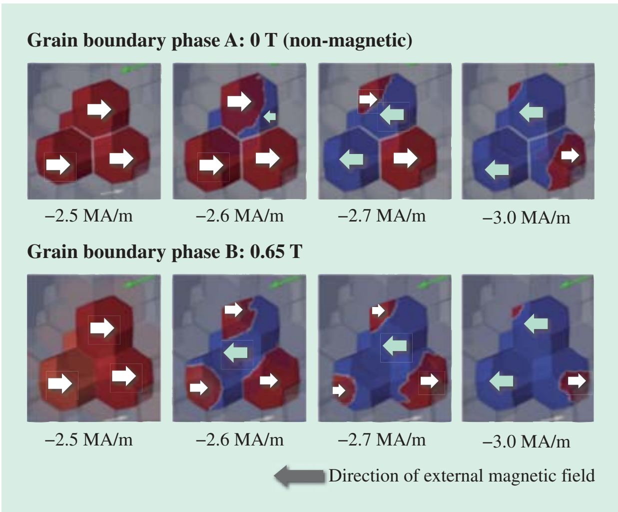

Fig. 9—Results of Calculating Magnetization Reversal Process Using Four-grain Model.
The region where magnetization reversal has occurred (blue regions with left arrows) grows as the external magnetic field increases. The progress of magnetization reversal is faster for case B (grain boundary phase is ferromagnetic) than for case A (grain boundary phase is non-magnetic).

handed magnetization). The behavior is consistent with the magnetization reversal measurements for single-crystalline grains described previously, namely that the grains contain two magnetic domains (with left- and right-handed magnetization respectively) separated by a domain wall that moves over time. A comparison of the two cases A and B shows that magnetization reversal proceeds more easily in case B where the grain boundary phase is ferromagnetic.

Fig. 10 shows this process of magnetization reversal in the form of a magnetization curve. The vertical axis represents the sum of the magnetizations of the four-grain model normalized to the saturation magnetization of Nd-Fe-B. From Fig. 9, the right-handed component of magnetization is treated as positive and the left-handed as negative. The magnetic field at which the total magnetization becomes zero (the coercivity) is lower for case B than for case A.

As the measurements of the grain boundary phase magnetization made using the spin-SEM and the results of LLG simulation analysis both indicate that the grain boundary phase in a typical Nd-Fe-B magnet is ferromagnetic, this indicates that this magnetization is a cause of lower coercivity. Furthermore, LLG simulation analysis indicates that reducing the magnetization of the grain boundary phase and increasing its thickness will improve coercivity.

DEVELOPMENT OF DY-FREE MAGNET[4]

Noting that the grain boundary phase is a major factor in improving coercivity, Hitachi Metals succeeded in significantly reducing Dy content by studying the range of compositions and alloying elements in ways that had not previously been considered, and by various fine tuning, including of the manufacturing conditions.

The new magnets were released in April 2014 as the NEOMAX Low Dy Series, with the product range extending from the NMX-46F to the 35F, and have been increasingly adopted for use. The magnets have similar remanent magnetic flux density (B_r) and coercivity (H_{cJ}) to the previous NMX-50 Series but a significantly lower mass-percentage (mass %) of Dy (mass of Dy as a percentage of the mass of the entire magnet) (see Fig. 11). For example, the 46F is "Dy-free," with similar characteristics to previous magnets despite only containing approximately 2% Dy by mass. Hitachi Metals has also developed a range of low-Dy magnets (NMX-S49F to S38F) similar to its previous NMX-S52 Series of high-performance magnets. These entered mass production in FY2015.

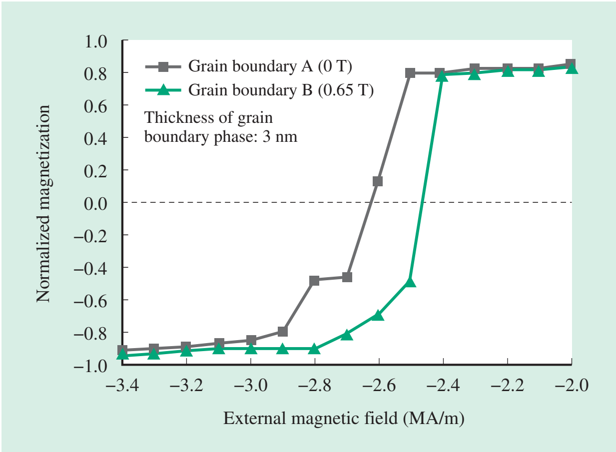

Fig. 10—Results of Calculating Magnetization Curve Using Four-grain Model.
Magnetization reversal is initiated at a lower external magnetic field (coercivity is lower) for case B (grain boundary phase is ferromagnetic) than for case A (grain boundary phase is non-magnetic).

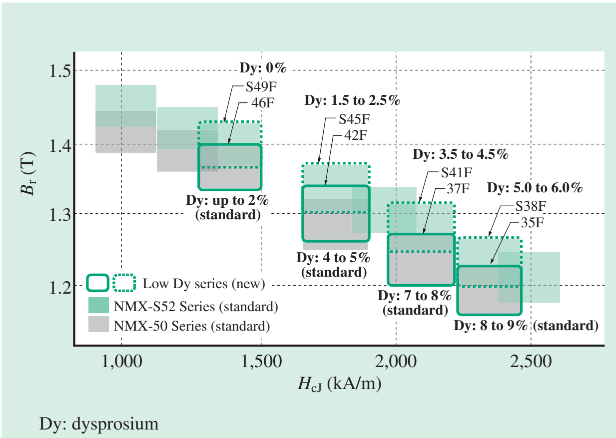

Fig. 11—Characteristics Map of Dy-free Nd-Fe-B Magnet[4].
Hitachi has developed magnets that maintain high performance despite using significantly less Dy.

CONCLUSIONS

Permanent magnet materials such as Nd-Fe-B play an essential role in underpinning Hitachi's social infrastructure business. While it goes without saying that ongoing material identification and process development based on the accumulation of knowledge and experience in materials science is vital for developments like this, it is also becoming more and more necessary in today's increasingly competitive environment to analyze the phenomena that govern performance and use this to suggest ways of improving characteristics, and to incorporate this knowledge into materials design, as described in this article. The Research & Development Group intends to continue contributing to materials development at Hitachi by making further advances in analysis techniques that combine materials analysis, magnetism measurement, and simulation.

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Featured Articles

Vehicle-level Analysis Technique for EMC Design of Automotive Inverters

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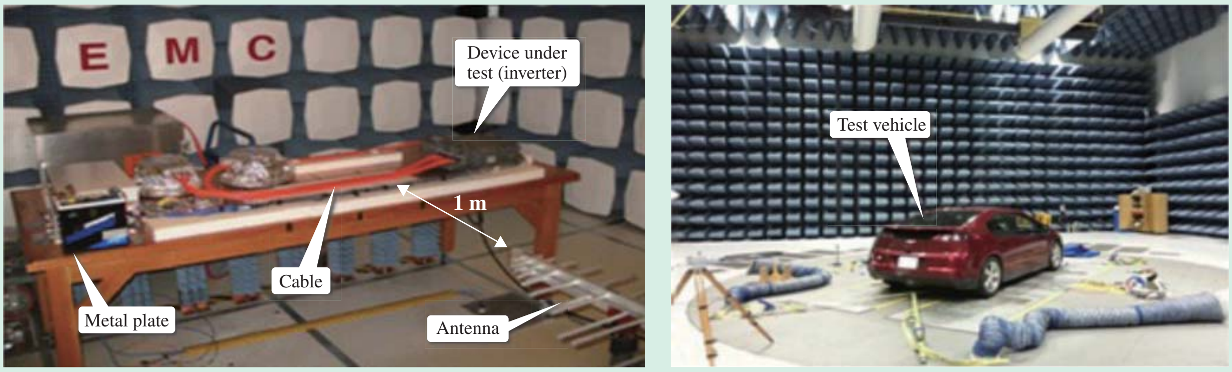
Hideyuki Sakamoto
Ryuichi Saito

OVERVIEW: To ensure vehicle safety and comfort, there is a need to minimize interference due to electromagnetic noise from automotive electronics. While automotive manufacturers have stipulated EMC standards for this purpose that component suppliers are obliged to comply with, there are cases when additional measures are needed to satisfy EMC requirements for the vehicle as a whole even though its individual components comply with the EMC standards, as the behavior of electromagnetic noise varies depending upon the installation conditions. This happens because the amount of noise generated changes when the electronics components are installed onboard. In response, Hitachi has developed a vehicle-level analysis technique that can predict electromagnetic noise for the completed car in which the electronic components are installed, thereby enabling EMC countermeasures to be incorporated into the design at an upstream design level, rather than added reactively. To enable the technique to predict the level of noise with sufficient accuracy for use in design (within ±12 dB), it splits the vehicle analysis into three separate parts in order to reduce the dynamic range that each one needs to deal with, thereby making it possible for the full analysis to deal with the wide dynamic range in the level of electromagnetic noise detected by a vehicle-mounted antenna, from the drivetrain inverter with a high power output (kW) down to tiny μW-level radiation. By adopting this approach, Hitachi believes it can successfully perform EMC design for the completed vehicle at the component design stage.

INTRODUCTION

THE number of electronic components used in vehicles has increased over time along with greater electrification and technical progress in data network connectivity. To ensure that the electromagnetic noise generated by these components does not interfere with the operation of other devices, such as car radios, manufacturers of automotive electronics conduct electromagnetic compatibility (EMC) testing of individual components and vehicle manufacturers conduct testing of completed vehicles[(1), (2)].

Fig. 1 (left) shows an example of EMC testing of an automotive inverter. The test determines the level of radiated emissions by placing the inverter, cable, and other components on a metal plate that simulates the vehicle chassis and measuring the voltage induced in an antenna positioned nearby. Test conditions such as the position of the cable and measurement antenna are stipulated in the International Special Committee on Radio Interference 25 (CISPR 25) international standard. In the case of radiated emissions testing, for example, this specifies measuring the induced voltage in an antenna placed 1 m from the cable. Vehicle testing, in contrast, is performed using a production-model vehicle (see Fig. 1 right). Vehicle EMC testing is broadly divided into radiated emissions testing that measures the induced voltage in an antenna positioned outside the vehicle, and interference testing on vehicle-mounted antennas such as that used by the car radio. In these tests, however, the conditions for the generation and propagation of electromagnetic noise differ widely from vehicle to vehicle due to factors such as antenna location and vehicle body shape. Although careful study is undertaken before performing standalone EMC testing of components in order to replicate actual onboard installation conditions, the EMC behavior still does not necessarily match that on the actual vehicle.



EMC: electromagnetic compatibility

Fig. 1—EMC Testing of Automotive Electronics (Left) and Vehicle (Right).
EMC testing of electronic components is performed using a cable and antenna in accordance with a standard. As vehicle testing uses a production-model vehicle, the conditions for the generation and propagation of electromagnetic noise differ from vehicle to vehicle and therefore the results do not always match those of individual component testing.

Consequently, even if a component itself passes EMC testing, there is a risk that electromagnetic interference problems will still be found on vehicle-mounted antennas during vehicle EMC testing. Because vehicle EMC testing is not normally performed until after component testing, if it turns out that modifications are needed, this imposes additional costs or delays due to design changes to the component or vehicle. This results in considerable losses not only to the automotive electronics manufacturer but also the vehicle manufacturer.

In response, Hitachi has worked with General Motors Company (GM) in the USA to develop an EMC analysis model for completed vehicles (including the inverter) that can be used to predict the level of electromagnetic noise from electronic components onboard. The work included verification testing on actual vehicles. The ability to predict—at the component design stage—the level of electromagnetic noise that those components will emit when installed in the vehicle makes it possible to produce low-noise designs (see Fig. 2). The research was targeted at use on GM's electric vehicle Volt that is equipped with two motors, high-voltage batteries, high-voltage shielded cables that connect to the batteries, and a drivetrain inverter that is made by Hitachi. The model was suitable for analysis of the electromagnetic noise from the inverter installed in the vehicle.

MECHANISM OF ELECTROMAGNETIC NOISE GENERATION BY INVERTER

The drivetrain inverter in a hybrid electric vehicle uses switching of insulated-gate bipolar transistors (IGBTs) or similar semiconductors to convert several hundred volts of direct current to the alternating current that drives the electric motor. Although the semiconductors operate at a switching frequency in the order of kHz, the

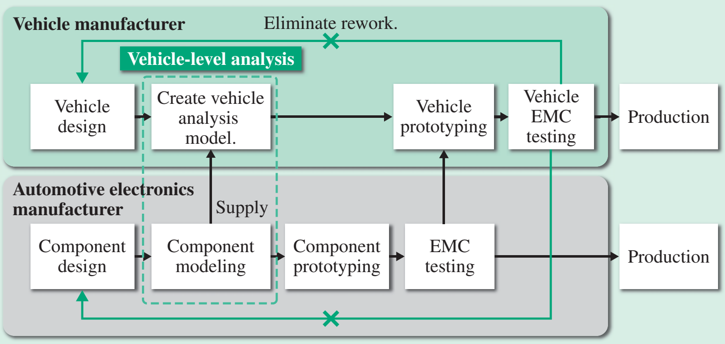


Fig. 2—Development Process for Automotive Electronics and Vehicles.
Because vehicle EMC testing is not performed until after component EMC testing, any problems with noise result in additional costs and delays due to design changes.

high-frequency components generated during voltage switching extend up to the MHz range. Furthermore, whereas an inverter has an output in the kW range, because preventing interference due to the leakage of electromagnetic noise requires that this noise level be considerably low (in the μW range or less), it is standard practice to use shielded cables for connecting between the inverter, motor, and high-voltage batteries.

VEHICLE-LEVEL EMC ANALYSIS

The technical challenge posed by vehicle-level EMC analysis is to conduct a precise analysis over a wide dynamic range that extends from the high-power (kW range) operation of the inverter to very low levels of radiated emissions (μW range). The difficulty is that an analysis over this wide dynamic range needs to be accurate over nine orders of magnitude (180 dB), which is difficult to achieve through normal analysis of this nature that deals with only three orders of magnitude (60 dB). Accordingly, a sequential vehicle-level analysis was developed to overcome this problem based on an assumed mechanism whereby radiated emissions are generated by leakage currents in the vehicle body[3]. This involved improving accuracy by dividing the analysis into three stages in order to minimize the dynamic range that each analysis needed to deal with: (1) inverter switching analysis, (2) leakage current analysis, and (3) radiated emissions analysis (see Fig. 3).

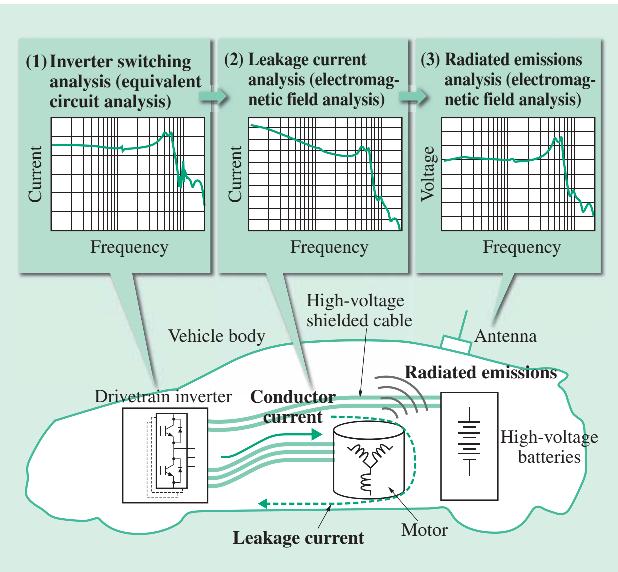


Fig. 3—Vehicle-level Analysis.
A high level of accuracy is achieved by splitting vehicle-level analysis into three parts.

The following section describes these separate analyses. First, an equivalent circuit analysis is used to calculate the high-frequency components (I_N) of the motor drive current output by the inverter. Next, electromagnetic field analysis is used to calculate how much of the high-frequency current (I_N) generated by the high-speed inverter switching leaks to the vehicle body. As the leakage current distribution is determined by the shape of the metal in close vicinity to the cable, the analysis only covers this narrow region. This determines the proportion (K_1) of the inverter output current that leaks to the vehicle body (leakage current coefficient). The third step is to determine the level of interference at the antenna due to electromagnetic noise generated by the leakage current in the vehicle body. This is done using an electromagnetic field analysis of the propagation of noise inside and outside the vehicle and the antenna induced voltage, treating the leakage current as the excitation source. This analysis provides the radiated noise propagation coefficient (K_2) from the leakage current to the vehicle-mounted antenna. By using these analyses to obtain the inverter output current (I_N), leakage current coefficient (K_1), and noise propagation coefficient (K_2), the induced voltage in the vehicle-mounted antenna (V_A) can then be calculated (equation 1).

$$V_A = I_N \times K_1 \times K_2 \tag{1}$$

By focusing on the known mechanism whereby radiated emissions are generated by the high-frequency leakage current, and by separating the vehicle-level analysis into parts, the dynamic range of power levels dealt with by each analysis is kept below three orders of magnitude (60 dB). This enables a high-precision analysis to be performed using standard electromagnetic field analysis software. Furthermore, if a design change consists of shifting the antenna only, it is sufficient to only re-perform the analysis for the noise propagation coefficient (K_2). Accordingly, this approach also improves the efficiency of the analyses, which need to be performed numerous times during the early design stage.

Fig. 4 shows the vehicle model used for the noise propagation coefficient (K_2) analysis. A monopole EMC testing antenna is used for testing. Meanwhile, to verify that the method is suitable for vehicle-level analysis, analyses were performed for two separate antenna locations (on the roof and on the front of the vehicle) and the results compared with actual measurements.

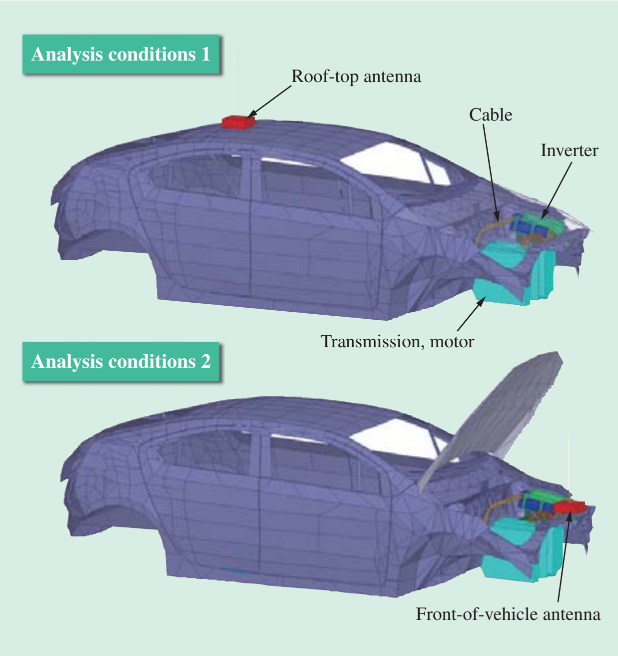


Fig. 4—Radiated Emissions Analysis Model.
The vehicle-level analysis was performed for two antenna locations to perform analytical verification of the induced voltage due to noise at different antenna locations.

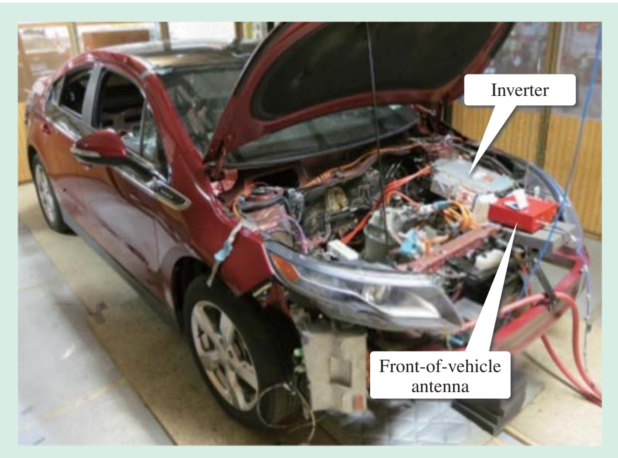


Fig. 5—Specially Prepared Vehicle for EMC Measurement.
The voltage induced in the antenna during inverter operation was measured on an actual vehicle.

MEASUREMENT

Fig. 5 shows the vehicle that was specially prepared for conducting the electromagnetic noise measurements by removing electronic components other than the drivetrain inverter that was the subject of the test. This was done to prevent noise from these other components from influencing the results. The antenna for measuring radiated emissions was positioned at the same locations as in the analysis (on the roof and on the front of the vehicle) and the induced voltage in the antenna measured using special-purpose test equipment. All measurements were performed in a shielded room to prevent disturbances due to external noise.

PREDICTED VS. ACTUAL RESULTS AND DISCUSSION

A comparison was made of the predicted and actual results for the frequency characteristics of the induced voltages measured at the two antenna positions (see Fig. 6). The peak noise frequency was 6 MHz when the antenna was located on the roof and 7 MHz when it was on the front of the vehicle, with errors between predicted and measured values of 3 dB and 7 dB at the two respective frequencies indicating good agreement. Possible causes of error in the high-frequency range above 10 MHz include simplification of the vehicle.

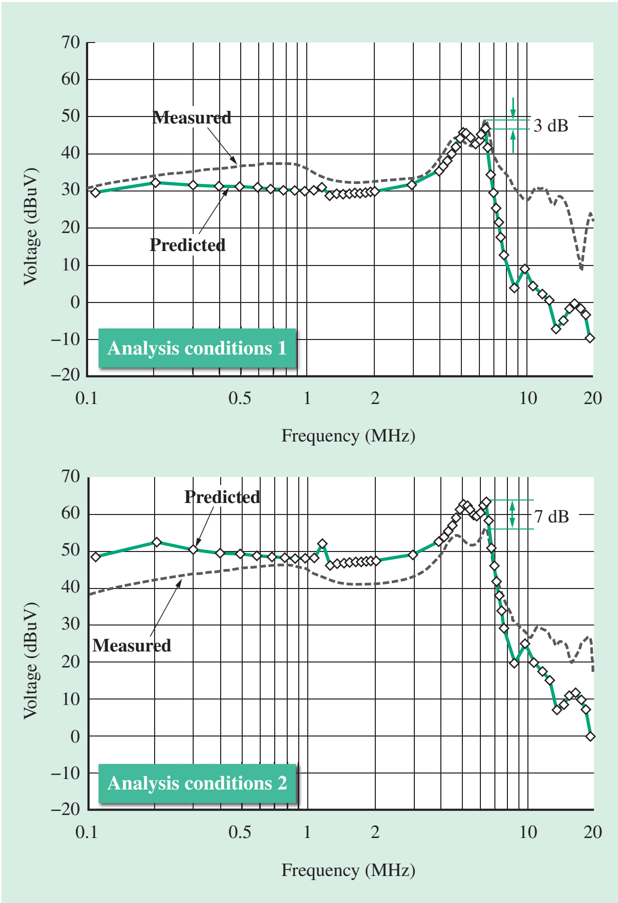


Fig. 6—Comparison of Analysis and Measurement of Radiated Emissions.
The comparison indicated an error in the predicted maximum noise levels of approximately 7 dB, and confirmed the frequency characteristics of the antenna induced voltage and the differences in induced voltage due to location.

Furthermore, in the case of vehicle-level analysis, it is important to verify the accuracy of both the noise source and vehicle models because the errors due to these are added up.

CONCLUSIONS

Hitachi has developed a vehicle-level EMC analysis technique so that countermeasures against electromagnetic noise can be built into automotive electronics in the upstream stage of design process. Although the analysis covers a wide dynamic range (180 dB), predictions of the level of interference at vehicle-mounted antennas can be made with sufficient accuracy for practical component design (within ±12 dB) by splitting the analysis into three parts to minimize the dynamic range dealt with by each part. In the future, Hitachi intends to make use of this new technique in the EMC design of electronic components.

ACKNOWLEDGMENTS

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Featured Articles

Development of Compact Proton Beam Therapy System for Moving Organs

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OVERVIEW: The use of particle beams in treating cancer, both in Japan and overseas, is growing in recognition of their ability to precisely target the dose of radiation on the cancerous tumor while minimizing the impact on surrounding organs. In particular, it is anticipated that particle therapy using scanning irradiation will become mainstream in the future. Having led the world in the commercialization of this form of treatment, Hitachi has also been working on the development of compact particle therapy systems that have been designed specifically to use this method. In 2009, as part of the "Advanced Radiation Therapy Project Real-time Tumor-tracking with Molecular Imaging Technique" funded by the FIRST Program as a national project launched in partnership with Hokkaido University, Hitachi jointly developed and commercialized a scanning irradiation technique that can track moving organs, and that incorporated a tumor-tracking radiotherapy system developed by Hokkaido University. Hitachi intends to utilize these new technical developments to help encourage the wider adoption of particle therapy.

INTRODUCTION

THE use of radiation in cancer therapies has become increasingly important in recent years as a form of treatment that can improve the patient's subsequent quality of life (QoL). Particle therapy, in particular, which uses protons or carbon ions accelerated to a high energy, is seen as having significant potential, in terms of treatment effectiveness and the minimizing of side effects, due to its ability to focus a high proportion of the dose on the cancerous tumor. Currently particle therapy is offered by a total of 53 different facilities around the world, with more than 120,000 patients having received treatment to date. With further 32 facilities currently under construction and 17 more planned, it is anticipated that the technology will continue to proliferate in the future(1). Hitachi develops its particle therapy systems by utilizing technology built up through the development and manufacture of particle accelerators for use in physics research(2). Based on its success in supplying a proton beam therapy system to the Proton Medical Research Center at the University of Tsukuba Hospital, which commenced operation in 2001(3), Hitachi received an order in 2002 for a proton beam therapy system from the University of Texas MD Anderson Cancer Center (MDACC), which became the first commercial facility in the world to commence therapy using proton beam spot scanning irradiation technology in 2008(4), (5). Spot scanning irradiation technology is able to further enhance the ability of particle therapy to precisely target the dose. Meanwhile, recognizing the need to reduce overall system size and cost to encourage the wider adoption of particle therapy, Hitachi has continued to work on ways of achieving this since completing the MDACC system.

As part of the "Advanced Radiation Therapy Project Real-time Tumor-tracking with Molecular Imaging Technique," which was selected as a national project in 2009 and funded by the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program), Hitachi worked in partnership to incorporate the tumor-tracking radiotherapy system being developed by Hokkaido University that can perform radiotherapy on moving tumors. Fig. 1 shows photographs of the treatment room and synchrotron (main accelerator) of the completed molecular tracking proton beam therapy system, and also of the facility in which it is housed. The Hitachi proton beam therapy system supplied to Hokkaido University was approved for manufacture and sale as a medical device under the Pharmaceutical

(a) Treatment room (b) Synchrotron (c) Proton Beam Therapy Center

Fig. 1—Proton Beam Therapy System at Hokkaido University Hospital Proton Beam Therapy Center.
(a) Treatment room equipped with rotating gantry. The irradiation field shaping mechanism (located under the table) enables the proton beam to be directed at the patient from any angle (360°). (b) The proton beam is accelerated by a synchrotron accelerator. (c) The Proton Beam Therapy Center is located next to Hokkaido University Hospital for easy access by patients.

Affairs Act in February 2014, and proton beam therapy based on the scanning irradiation method commenced in March of that year. Approval for manufacture and sale as a medical device under the Pharmaceutical Affairs Act was also obtained for a therapy system that combines the tumor-tracking and spot scanning irradiation techniques in August 2014.

This article describes the development of a compact proton beam therapy system specifically designed for spot scanning irradiation, and the current progress on developing techniques for the precise irradiation of tumors that are in motion (due to the patient's breathing, for example).

MAKING PROTON BEAM THERAPY SYSTEM SMALLER

To irradiate tumors located deep in the body, proton beam therapy accelerates protons to about 70% of the speed of light. Hitachi uses a synchrotron for this purpose, a form of circular accelerator. Recognizing that reducing the size of the synchrotron is essential to reducing the size of the overall proton beam therapy system, Hitachi embarked on development with the aim of creating a system designed specifically for scanning irradiation.

A proton beam therapy system consists of a synchrotron (main accelerator), a linear accelerator that acts as the injector for the synchrotron, a high-energy beam transport line that directs the high-energy protons to the treatment room, a rotating gantry that can aim the proton beam at the patient from any direction, and an irradiation nozzle that shapes the proton beam to match the shape of the patient's tumor (see Fig. 2).

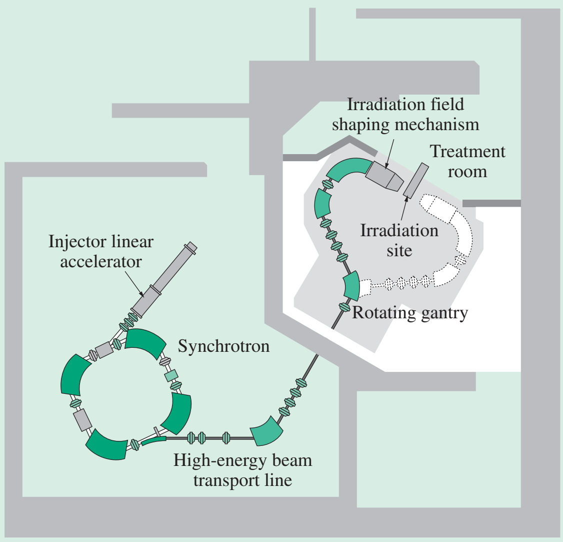

Fig. 2—Overall Structure of Proton Beam Therapy System.
Protons accelerated by the synchrotron are transported to the treatment room where the irradiation field shaping mechanism directs the beam at the tumor, shaping it to match the shape of the tumor.

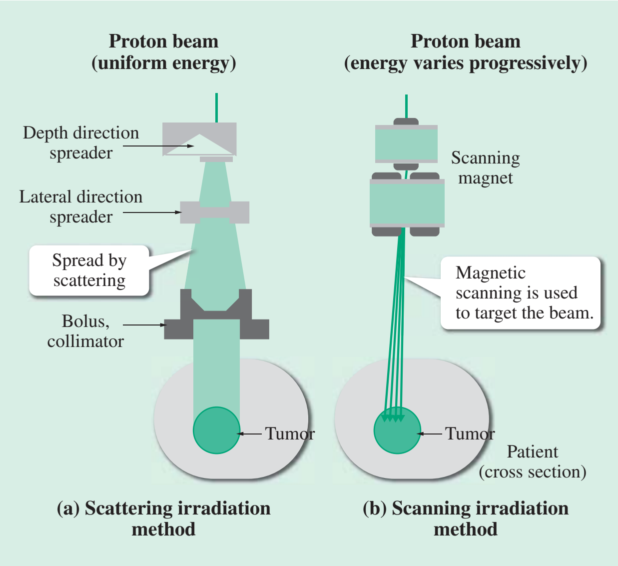

Fig. 3—Comparison of Systems for Shaping Irradiation Field.
Whereas the scattering irradiation method utilizes the energy loss that occurs as protons pass through a material to spread the proton beam in the depth direction and scattering to spread the beam in the lateral direction, in the scanning irradiation method, spreading the irradiation field over a three-dimensional region is performed entirely magnetically, resulting in low energy loss and high proton utilization.

Advantages of Spot Scanning Irradiation

Fig. 3 shows the designs of the systems that shape the irradiation field for radiotherapy using the previous scattering irradiation method and for the scanning irradiation method. In the case of the scattering irradiation method, the proton beam enters the irradiation field shaping mechanism with uniform energy. Here, the high dose rate region is enlarged using devices that spread the beam in the depth and lateral directions respectively, and the beam then passes through a beam-limiting collimator to match its cross-section to that of the tumor. Spreading the dose distribution in the lateral direction utilizes the principle whereby the proton beam scatters as it passes through a material, a process that is accompanied by a loss of energy. Because the collimator is used to block the unwanted part of this widened irradiation field, the proton utilization of this method is low. In contrast, spot scanning irradiation seeks to focus a narrow proton beam from the accelerator at the target without allowing its diameter to spread, and matches the dose distribution to the tumor shape by three-dimensional scanning of the irradiation site. The irradiation depth (in the direction of the proton beam) is adjusted by varying the energy to which protons are accelerated by the synchrotron, and two scanning magnets are used to magnetically scan the beam over the plane perpendicular to the beam direction. This results in a very high proton utilization, where close to 100% of the proton beam that enters the irradiation field shaping mechanism reaches the tumor. Consequently, the advantages of designing a system specifically for spot scanning irradiation are that there is minimal energy loss in the irradiation field shaping mechanism and high proton utilization. These were incorporated into the development of the compact accelerator system.

Development and Testing of Compact Accelerator System

The development of the compact accelerator system designed specifically for spot scanning irradiation took advantage of the minimal energy loss in the irradiation field shaping mechanism to down-rate the performance of the synchrotron (main accelerator) from the 250-MeV maximum energy of the previous system to 235 MeV. This reduced the required magnetic field performance of the various system components and the specifications of the power supply for the electromagnets used to produce the magnetic field. Similarly, Hitachi realized it could take advantage of the high proton utilization to reduce the intensity of the beam of accelerated protons extracted from each cycle of the synchrotron. Because utilization of these features gave Hitachi greater flexibility in the basic design of the synchrotron, Hitachi started out on the development with the idea of using a bare-minimum configuration, the end result of which was a basic layout that consisted of four linear sections linked by four 90° bending magnets (one linear section each for injection and acceleration and two for extraction). As a result, the new design has two fewer bending magnets than the six on the previous system. Similarly, whereas the previous synchrotron had 10 quadrupole magnets to provide adequate range for post-commissioning adjustment, the compact accelerator system has only four thanks to coupling a dispersion function to the magnetic fields generated at the end shapes of the bending magnets (see Fig. 4).

The three-dimensional magnetic field distributions at the ends of the bending magnets are particularly important for the new compact accelerator system. By obtaining precise estimates of the behavior of particles in the magnetic field from the bending magnet and utilizing this information in the magnetic pole design, Hitachi developed and implemented a simulation technique for particle trajectory tracking that could be used to verify the orbital stability of protons in the synchrotron based on the results of three-dimensional

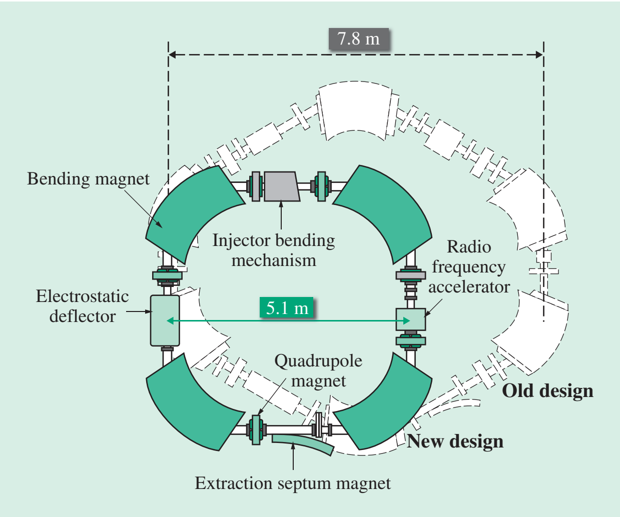

Fig. 4—Comparison of New and Old Synchrotron Designs.
By coupling the functions of the quadrupole magnets to the ends of the bending magnets, the new design has reduced the total number of main magnets (bending magnets and quadrupole magnets) to eight. This compares to 16 on the old design.

magnetic field analysis. This involved performing a three-dimensional magnetic field analysis over the range of the magnetic excitation field of the bending magnets to determine the magnetic field distribution in the region through which the protons pass and assessing the stability of the proton beam as the particles travel multiple times around the accelerator(6).

These developments were used for reference when performing on-site testing of accelerator performance. The testing started with the generation and acceleration of a proton beam from the linear accelerator that acts as the injector, and extended up to injection of the beam into the synchrotron, acceleration, and extraction. The fact that this process was completed in approximately one week demonstrates the usefulness of the simulation technique for particle trajectory tracking developed by Hitachi.

INCORPORATION OF TUMOR-TRACKING

A number of methods have been proposed for the radiotherapy of organs such as lungs and liver that move due to the patient's breathing and other movements. For the use of proton beam therapy to treat organs such as the lungs or liver, Hitachi supplied a respiration-synchronized irradiation technique in partnership with the Proton Medical Research Center at the University of Tsukuba Hospital(3). This uses a device for providing a respiration synchronization signal that detects the surface movement of the patient's body to obtain a respiration phase signal, and only outputs a gate signal when the movement reaches a predetermined phase. The proton beam is only output when this gate signal is on. The current development has involved combining Hitachi's spot scanning irradiation with tumor-tracking, a technique that has been developed by Hokkaido University to enable the radiotherapy of moving tumors(7). Tumor-tracking works by injecting a gold marker (1 to 2 mm in diameter) into the patient close to the tumor and obtaining X-ray images from two different directions at a rate of 30 frames per second to determine the location of the gold marker in the patient's body in three dimensions. The beam is then only output when the location of the marker is within a predefined range (see Fig. 5). The combination

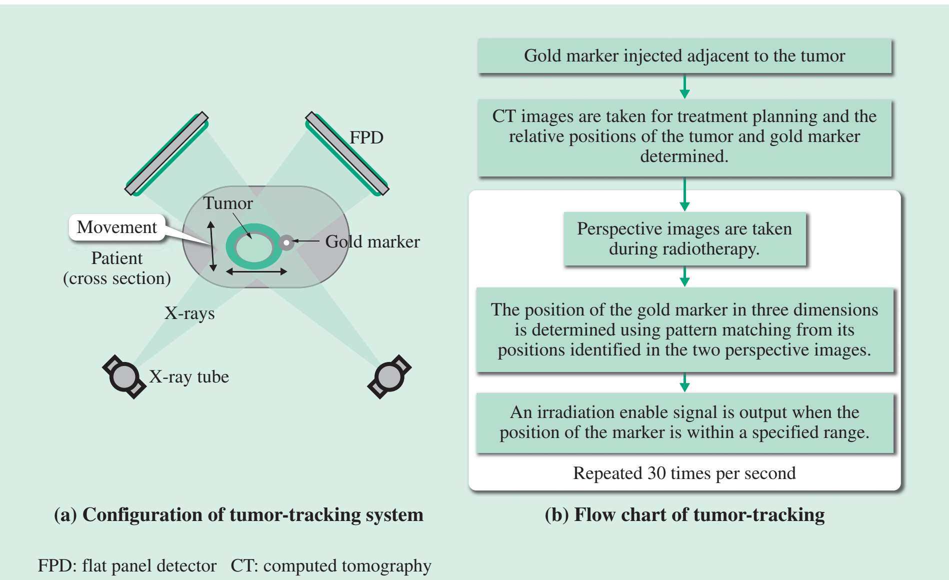

Fig. 5—Tumor-tracking.
(a) The system incorporates an X-ray imaging system that can obtain images of the patient from two different directions.
(b) A gold marker injected adjacent to the tumor is captured in the X-ray images and its position is determined in three dimensions using geometry based on its location above the detector (FPD). Because the position of the gold marker can be determined with high accuracy (within ±1 mm), it is possible to track the movement of the organ.

of tumor-tracking and spot scanning irradiation enables the movement of the tumor to be determined and ensures precise irradiation of moving organs.

Improvements in Accelerator Control

Hitachi has worked with a research team at Hokkaido University on the joint development of an accelerator operation control technique that improves irradiation efficiency on systems that combine tumor-tracking with spot scanning using a synchrotron accelerator. In this context, irradiation efficiency means the probability that the proton beam will be available when the signal from the tumor-tracking system specifies beam output. The operating practice that Hitachi adopted for the previous respiration-synchronized irradiation technique achieved efficient irradiation even if the respiration cycle varied by making the synchrotron operation cycle variable, switching operation to a standby mode after protons had been injected into the synchrotron and accelerated to the point where they were ready for extraction [see Fig. 6 (a)].

With tumor-tracking, on the other hand, a problem identified during discussions associated with the joint research was that, because the marker position can be determined 30 times a second, there is the potential for the irradiation enable signal to be turned on and off in short succession (33 ms), meaning that, if the previous operating practice is used, the proton beam will only be output for this very short time when irradiation is enabled, and the synchrotron accelerator will switch to deceleration. To prevent this, Hitachi has devised an operation and control technique that can maintain the quality of the delivered proton beam while still achieving a high irradiation efficiency. The technique utilizes a new delay gate during the control period after extraction starts that prevents the accelerator from switching to deceleration during short periods when the irradiation enable signal is off, but only after a fixed period of time has elapsed. This technique enables the synchrotron to be operated in such a way that multiple irradiation enable signals can occur within a single operation cycle [see Fig. 6 (b)].

The Hokkaido University research team has conducted testing of the irradiation enable gate signals for actual patients when using the previous tumor-tracking radiotherapy and found that the irradiation time that results from using this new control technique is about 20% shorter on average than for the previous method[8].

Testing Using Dose Distribution Calculation

By making enhancements to a dose analysis technique for scanning that has been the subject of ongoing development since commercializing spot scanning irradiation at MDACC, the dose distribution when using tumor-tracking in combination with spot scanning irradiation has been evaluated to verify the benefits. A target representing a tumor and consisting of a cube with 6-cm sides was placed in water used

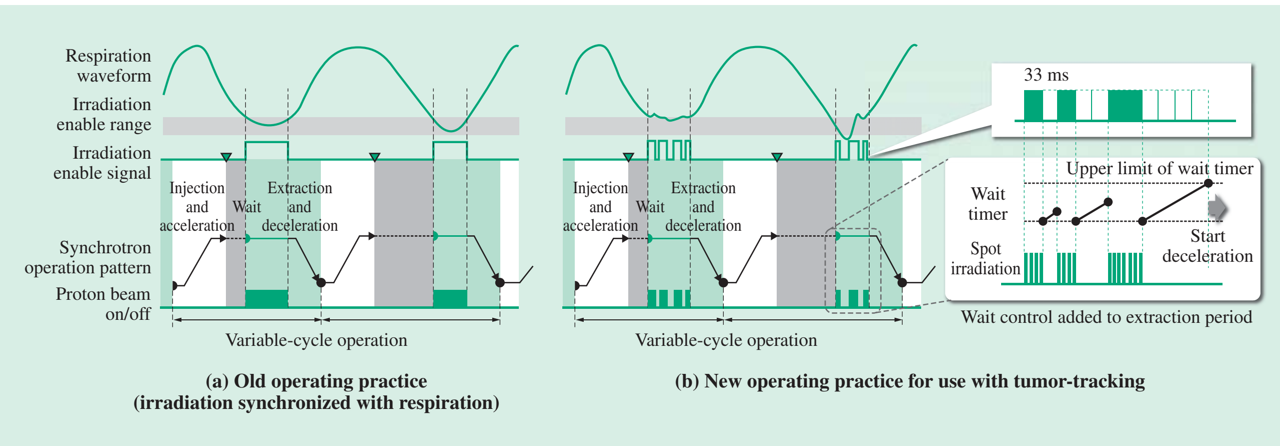

Fig. 6—Comparison of Old and New Synchrotron Operating Practices.
(a) The respiration-synchronized irradiation technique used in the past utilized the variable-cycle operation of the synchrotron to achieve highly efficient irradiation synchronized with the patient's breathing when the generated irradiation enable signal was comparatively long (less than 1 s). (b) Because the irradiation enable signal may be generated for periods as short as 33 ms (equivalent to determining of marker position 30 times per second) when combined with tumor-tracking, Hitachi improved irradiation efficiency by amending the operating practice to include standby control instead of decelerating immediately after the irradiation enable signal turns off, thereby enabling irradiation to occur multiple times during each operation cycle.

as a model of the human body and the irradiation conditions for delivering a uniform dose to the target were determined. Assuming that the movement of the target would follow a sine wave function raised to the fourth power with a peak-to-peak amplitude of 20 mm and a period of 3 s, the range of positions within that movement in which irradiation would be enabled was specified and a study was made of the relationship between the amplitude and the degree of uniformity of dose distribution within the target. Three directions of movement were specified: parallel to the preferred scanning direction for spot irradiation (primary direction), perpendicular to this direction (secondary direction), and the depth direction (direction of the proton beam) [see Fig. 7 (a)]. After first determining the dose distribution under each set of conditions, the dose uniformity was determined as follows based on the maximum and minimum doses in the target (D_{max} and D_{min}).

$$\text{Dose uniformity} = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

Using a 2-mm-wide irradiation enable range ensures a dose uniformity of within 3% of the intended value regardless of the direction of target movement [see Fig. 7 (b)].

To conduct testing under more realistic conditions, the Hokkaido University research team undertook a study using data from the respiratory movements of actual patients treated using the previous tumor-tracking radiotherapy technique or computed tomography (CT) data used for treatment planning. The study found that using tumor-tracking and spot scanning irradiation in combination resulted in precise irradiation of the tumor and identified the conditions for achieving this(9), (10).

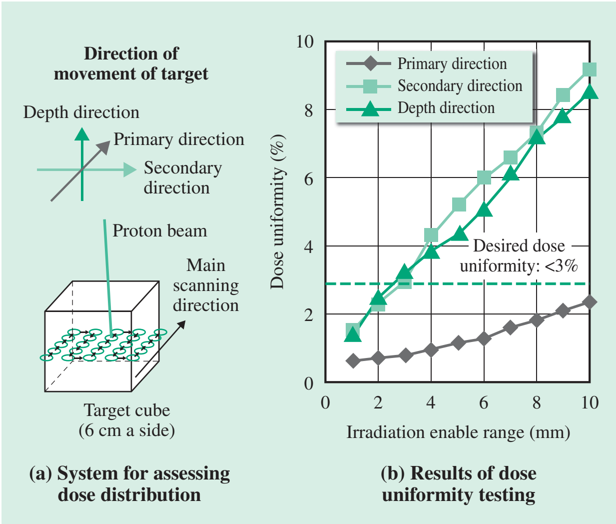

Fig. 7—Results of Dose Distribution Testing.
(a) The target cube was moved in a trajectory that mimicked respiration and the dose distribution determined. (b) Although performance differed depending on the scanning direction, the results indicate that the desired dose uniformity of 3% or less of the intended value can be achieved with an irradiation enable range of 2 mm.

EVALUATION OF PROTON BEAM RADIOTHERAPY PERFORMANCE

Testing was conducted to determine the performance at the point of irradiation for a proton beam from the synchrotron that had traveled to the treatment room via a high-energy beam transport line. When the position of the proton beam at the point of irradiation in the treatment room [see Fig. 8 (a)] was determined using measurements from a position monitor located in the irradiation field shaping mechanism, the error was less than 0.3 mm and the variability was low (1σ = 0.05 mm), indicating that the irradiation position can be controlled accurately [see Fig. 8 (b)].

The basic operation and dose distribution when using tumor-tracking and spot scanning irradiation in combination have already been determined, and work on testing the benefits of the control technique described above is ongoing.

CONCLUSIONS

This article has described the development of a compact proton beam therapy system designed specifically for spot scanning irradiation, and the progress being made on developing techniques for the precise irradiation of moving tumors (due to the patient's breathing, for example).

The compact proton beam therapy system was developed by designing it specifically for spot scanning irradiation. The development included use of a simulation technique for particle trajectory tracking that could verify the orbital stability of protons in the synchrotron accelerator based on the results of three-dimensional magnetic field analysis. The synchrotron (main accelerator) in the new system has a circumference of only 18 m, compared to 23 m for the previous system, and also has fewer main magnets. Hitachi has also developed an irradiation method that combines spot scanning irradiation technology with the tumor-tracking technology developed by Hokkaido University to provide proton

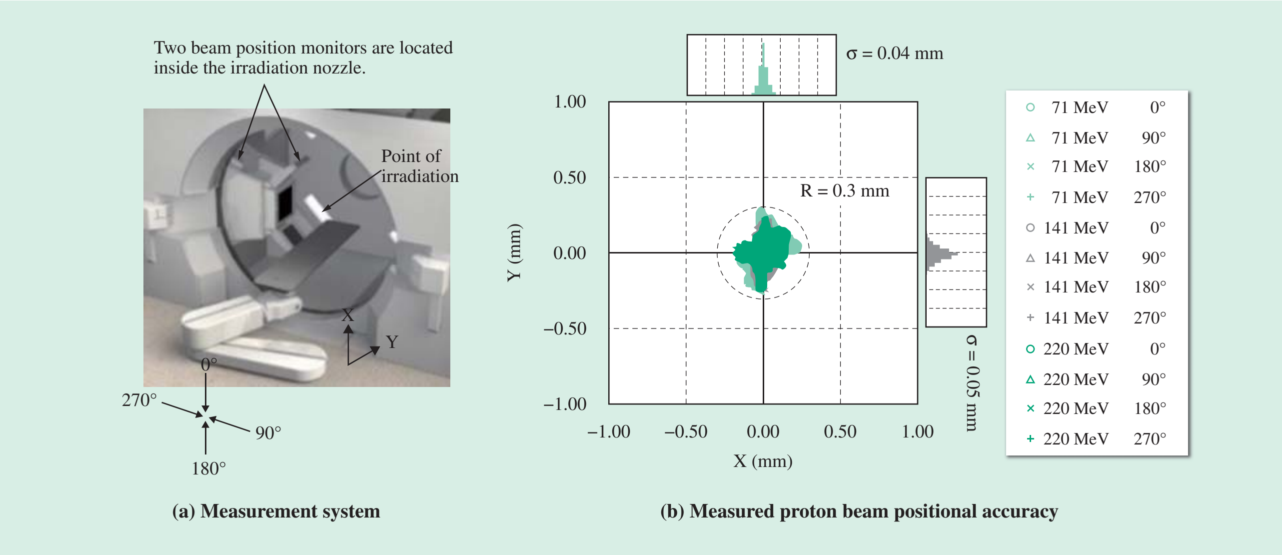

Fig. 8—Proton Beam Irradiation Performance Testing.
(a) To assess beam performance at the point of irradiation, the beam position was determined using measurements for each spot obtained by a beam position monitor located in the irradiation field shaping mechanism and the dose distribution was determined using a measurement device located at the point of irradiation. (b) The graph shows the results of testing from four different angles and at three typical energy levels, irradiating 2,000 spots each time.

beam therapy for tumors in organs that are moving (due to the patient's breathing, for example), and it has devised a synchrotron operating practice that improves irradiation efficiency.

In the future, Hitachi intends to contribute to the wider adoption of particle therapy by continuing with research and development aimed at building systems with smaller size and lower cost through the application of techniques developed through this research not only to particle beam therapy systems that use proton beams but also to those that use carbon ions.

ACKNOWLEDGMENTS

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Category Overview

Pioneering New Frontiers for Future Social Innovation
—Center for Exploratory Research—

ROLE OF CENTER FOR EXPLORATORY RESEARCH

THE role of the Center for Exploratory Research is to identify research topics that will help overcome the challenges that society will face in the future, to undertake leading-edge research and development from a long-term perspective, and also to create future opportunities for the Social Innovation Business by working as a global open laboratory with research institutions around the world.

To ensure the ongoing growth of society, customers, and Hitachi, it is important to undertake research based on an innovative vision that addresses both the inescapable societal challenges that have already become apparent, and those unknown challenges for the future of which society and customers are not yet aware. Having formulated a vision of "transforming social systems by pioneering new frontiers through exploratory basic research," the Center for Exploratory Research has embarked on the following two missions (see Fig. 1).

(1) Serve as hub for a network of basic research

Establishing a network that encompasses leading research institutions and top researchers is essential to the formulation and realization of the center's vision. Accordingly, it intends to adopt a rigorous approach to open innovation and expand its research network through links with the world's leading researchers forged by making available its own leading-edge research facilities, proprietary technologies, and other resources. It also aims to become an influential organization that can coordinate national projects and consortiums and contribute to policy.

(2) Take up the challenge of creating a new Social Innovation Business

The center will anticipate the true nature of future societal challenges and pioneer new businesses without being restricted to its current scope of activities. This involves collaborative creation with non-Hitachi institutions to uncover advanced societal challenges, and undertaking proof of concept (PoC) projects to present social impact and value. It also includes working to build the future Social Innovation Business through collaboration with the Global Center for Social Innovation and Center for Technology Innovation.

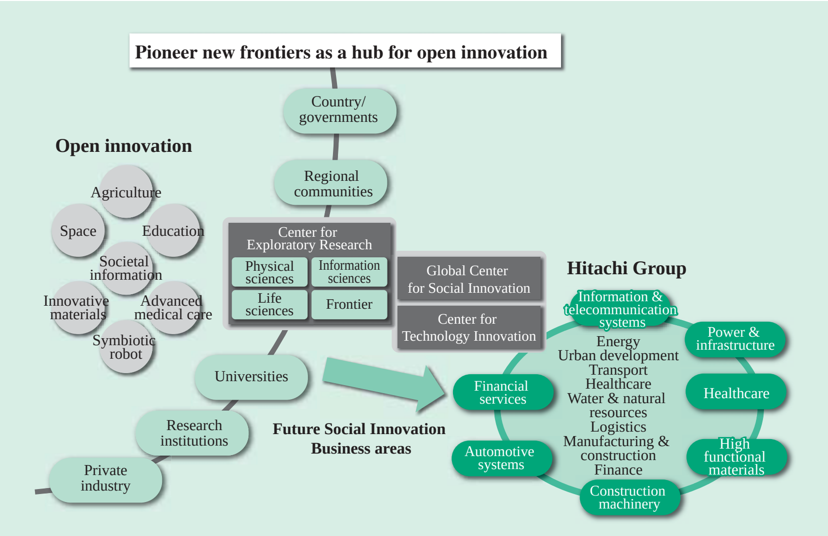

Fig. 1—Center for Exploratory Research.
The role of the Center for Exploratory Research is to serve as the hub for a basic research network, forge links with universities and external research institutions, and create future opportunities for the Social Innovation Business.

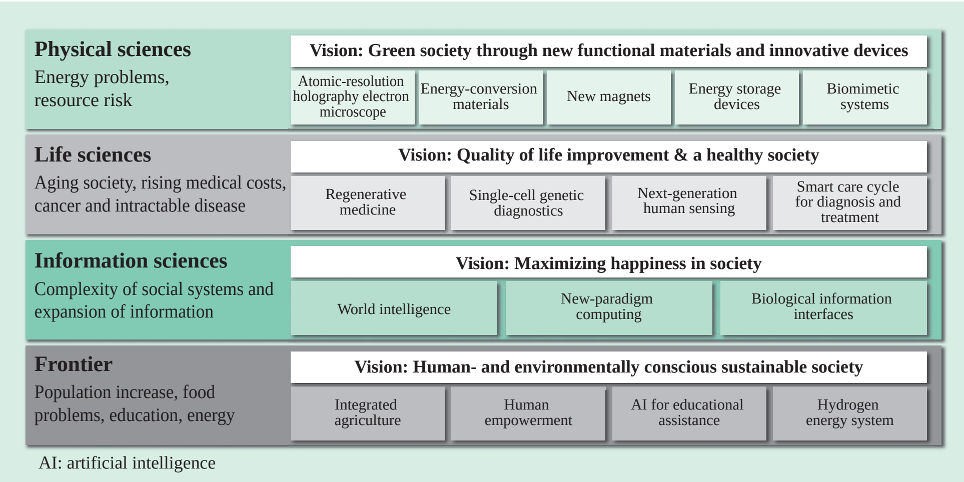

Fig. 2—Research Fields of Center for Exploratory Research.
The Center for Exploratory Research conducts research into four fields: the physical sciences, life sciences, information sciences, and the "frontier" field.

ORGANIZATION AND RESEARCH TOPICS

The Center for Exploratory Research has created a flexible and dynamic research organization by adopting a flat structure in which all projects report directly to the General Manager. Research is divided into four fields: physical sciences, life sciences, information sciences, and "frontier," with each field being fronted by a chief scientist who acts as the "face of Hitachi" and who leads research in that field. The following sections describe each of these fields in turn (see Fig. 2).

Physical Sciences

With a vision of "creating a green society through new functional materials and innovative devices," the center's work on physical science will involve the use of advanced measurement techniques to elucidate physical phenomena and develop new materials, and research into devices based on new principles and the systems that use them. Through these activities, the center aims to be a world leader in basic research, and to realize a green and ecological society through the creation of innovative materials and device systems. For example, the center aims to link up with physical science researchers from around the world to work on elucidating poorly understood physical phenomena by utilizing the ability of the atomic-resolution holography electron microscope[1] to observe magnetic fields with atomic resolution. This includes transforming the process of materials development by using the technology to study the principles that govern the material properties of magnets, energy-conversion and storage materials, and so on.

Life Sciences

In the life sciences, the center is pursuing a vision of "quality of life improvement & a healthy society." This involves working on research in the fields of regenerative medicine, single-cell genetic diagnostics, next-generation human sensing, and smart care cycles for diagnosis and treatment that seeks to overcome such challenges as the aging society, rising medical costs, cancer, and intractable disease. In the case of research into regenerative medicine, for example, the center is seeking to transform healthcare and create a healthy society by deploying an automated cell culture technique[2] jointly developed with Tokyo Women's Medical University for the automatic culturing of induced pluripotent stem (iPS) cells, as well as through comprehensive work in this field. With regenerative medicine expected to grow into a 17-trillion yen market by 2030, the center is also working on developing technologies that will make Hitachi a major player in this field.

Information Sciences

In the information sciences, the center is pursuing a vision of "maximizing happiness in society via artificial intelligence (AI) for assisting education" by working on research into "world intelligence," new-paradigm computing, and biological information interfaces to deal with challenges that include increasingly complex social systems and the expansion of information. "World intelligence" seeks to resolve complex societal challenges by using a harmonious combination of social science and artificial intelligence to drive the co-evolution of people, organizations, and artificial intelligences[3].

In the field of new-paradigm computing, the center is researching new computing concepts that can obtain rapid solutions to optimization problems for complex social infrastructure systems that would take a very long time to solve using conventional computing(4).

Frontier

In the "frontier" field, the center has a vision of "realizing a human- and environmentally conscious sustainable society," and is working on research into integrated agricultural production practices, human empowerment, AI for educational assistance, and a hydrogen energy system. Work in these fields involves seeking to overcome challenges such as population increase, food supply problems, education, and energy that society will face in the future by combining technologies from a variety of scientific disciplines.

FUTURE ACTIVITIES

In the future, the Center for Exploratory Research aims to deepen its links with leading researchers and with other non-Hitachi research institutions in Japan and overseas based around its one-off measurement instruments such as the atomic-resolution holography electron microscope, and its proprietary technologies such as automated cell culturing, human big data analytics, and Ising computers. Along with progress on establishing a basic research network, the center also intends to boost Hitachi's presence by taking a stronger stance on presenting its vision and research results outside the company. Through these initiatives, the center aims to pioneer new frontiers and build the future Social Innovation Business.

ACKNOWLEDGMENTS

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Featured Articles

Measuring Happiness Using Wearable Technology

—Technology for Boosting Productivity in Knowledge Work and Service Businesses—

Kazuo Yano, Dr. Eng.
Tomoaki Akitomi
Koji Ara, Dr. Eng.
Junichiro Watanabe, Dr. Eng.
Satomi Tsuji
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Miki Hayakawa
Norihiko Moriwaki, Dr. Eng.

OVERVIEW: Instead of the industrial production, which drove economic growth in the 20th century, the driver for growth in the 21st century is productivity in knowledge work and service businesses. For this reason, the authors developed a technique for measuring happiness using wearable technology. The research found a hidden signal representing a person's happiness within the basic pattern of physical activity known as the "1/T rule." This result uncovered a close relationship between the "trinity" of physical activity = happiness = productivity. Combined with a technique for using artificial intelligence to generate KPIs automatically, the technology can foster the ability of groups to engage in "co-creation" while also encouraging autonomy and commitment in individuals. This new technology is recognized as having the potential to open up new pathways in corporate accounting, production, and human resource systems.

INTRODUCTION

It has long been said that enhancing the productivity of knowledge work and service businesses will be key to future economic growth. However, it is not clear how to do this, and no successful examples are evident. Attempts have been made to apply techniques that have proven successful in manufacturing, such as industrial engineering and the Toyota Production System, to knowledge and service businesses. However, the fundamental differences between the manufacturing workplace, where operational processes and deliverables are clearly defined, and the service workplace mean that the simplistic application of such techniques has failed to produce results. Similarly, while practices such as management accounting (including budgeting and cost management) and human resource systems (including management by objectives and evaluations) might also be expected to improve productivity, these too have failed to deliver significant benefits.

Does this mean it is impossible to make fundamental enhancements in the productivity of knowledge work and service businesses? No—and in fact, wearable technology has the potential to make this possible. The use of wearable technology opens up possibilities for the quantification and control of human and social activities that have previously been understood only in qualitative terms. The technology will transform corporate accounting, production, and human resource systems at a fundamental level.

QUANTIFYING HAPPINESS

What the authors chose to look at was people's wellbeing or happiness. At first glance, these may appear to be questions more suited to philosophy or religion. Recently however, various countries, including not only Japan but also the UK, France, Austria, and Bhutan, have considered adopting happiness as an alternative national indicator to gross domestic product (GDP). The Ministry of Education, Culture, Sports, Science and Technology even has a research project in progress aimed at achieving a "Happiness Society."

It has been reported that a person's happiness significantly influences performance. Compared to people who are unhappy, it has been found that people who are happy have 37% higher work productivity and 300% higher creativity[1]. They also enjoy higher annual income, faster promotion, and are more likely to have a successful marriage, have friends, and to live longer and healthier lives[2]. It has also been reported that companies with a large number of happy people have higher earnings per share.

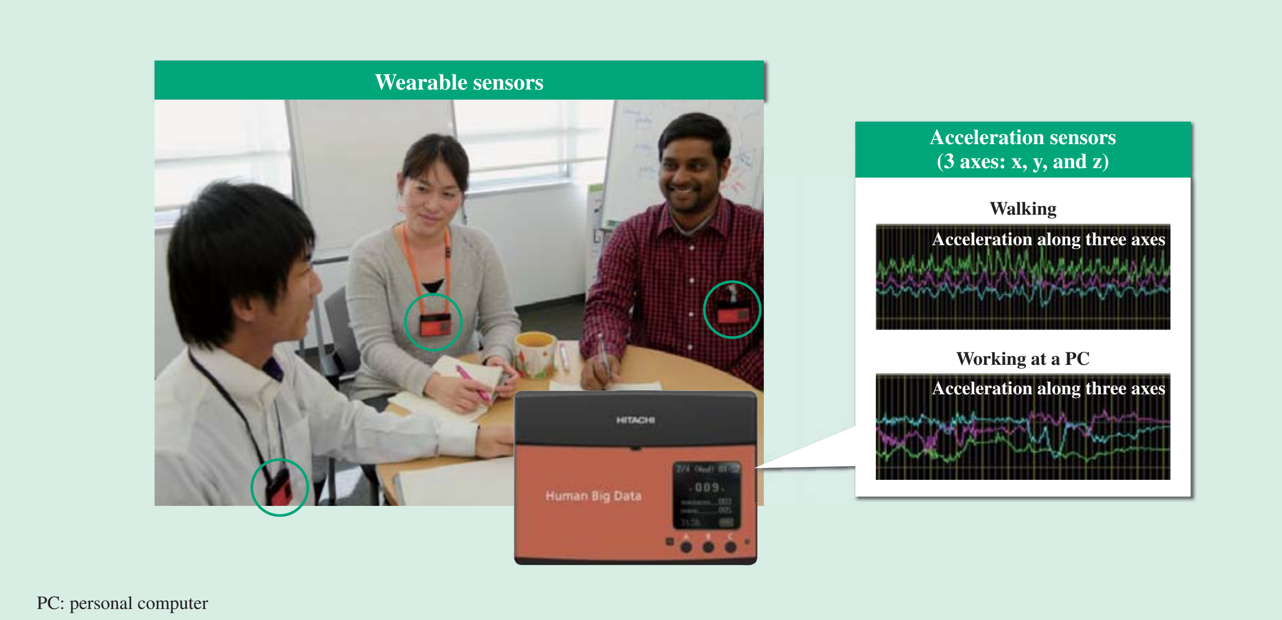

Fig. 1—Identification of Correlation between Group Happiness and Patterns of Physical Activity Measured by Wearable Sensors.
Group happiness can be measured in realtime simply by wearing a sensor. Physical activity is measured using three-dimensional acceleration data.

The important point is not that successful or healthy people are happy, but that happy people have a higher likelihood of being successful and healthy. It has also been found that the contribution of success and health to happiness is only 10%[(2)].

Meanwhile, mental health problems in the workplace have a major impact on employee productivity. The number of people suffering from depression or other mental illness has more than doubled over the last 15 years, with sick leave and the effect on the people around them having a significant effect on productivity.

The problem with this, however, is that it is not possible to quantify happiness. While questionnaires have been used for measuring happiness, the wide range of between-individual variance in questionnaire responses means that these are subjective and suffer from a lack of plausibility and repeatability.

So, is there any way to define, measure, and quantify happiness as if it were a measurable quantity from one of the hard sciences?

Hidden Relationship between Physical Activity and Happiness

Over the span of nine years, Hitachi has collected and studied more than a million days' worth of data on people's activities using wearable technology[(3), (4), (5)]. Using data from wearable sensors with millisecond resolution, the authors have identified characteristic patterns of physical activity that have a strong correlation with happiness. The sensors take the form of a card attached to the chest that can record measurements of the amount and direction of movement in three dimensions and with high resolution (50 times a second, or once every 20 ms)[(6), (7), (8)] (see Fig. 1).

From this vast amount of data, the authors uncovered a fundamental rule that relates to physical activity. This is the "1/T rule"[(9)]. It categorizes physical activity during each unit of time as either inactive or active, and looks at the "active" times when the person is moving and how long they last (called "sustained activity"). Activities categorized as "active" include not only walking, but also small movements such as nodding or typing. The duration (T) of sustained activity has a wide variance depending on the circumstances. What is found when looking at the distribution of T values within a group is that it follows not the "bell curve" normal distribution, but rather a long-tail distribution. Typically, 30% of sustained activity instances account for 70% of all physical activity, with activity being skewed toward certain times or people. The name of the "1/T rule" derives from the fact that, quantitatively, the probability of changing to inactivity is inversely proportional to T, and accordingly, the fluctuation in physical activity is called "1/T fluctuation"[(10), (11), (12)] (see Fig. 2). This can be thought of as the human version of Newton's first

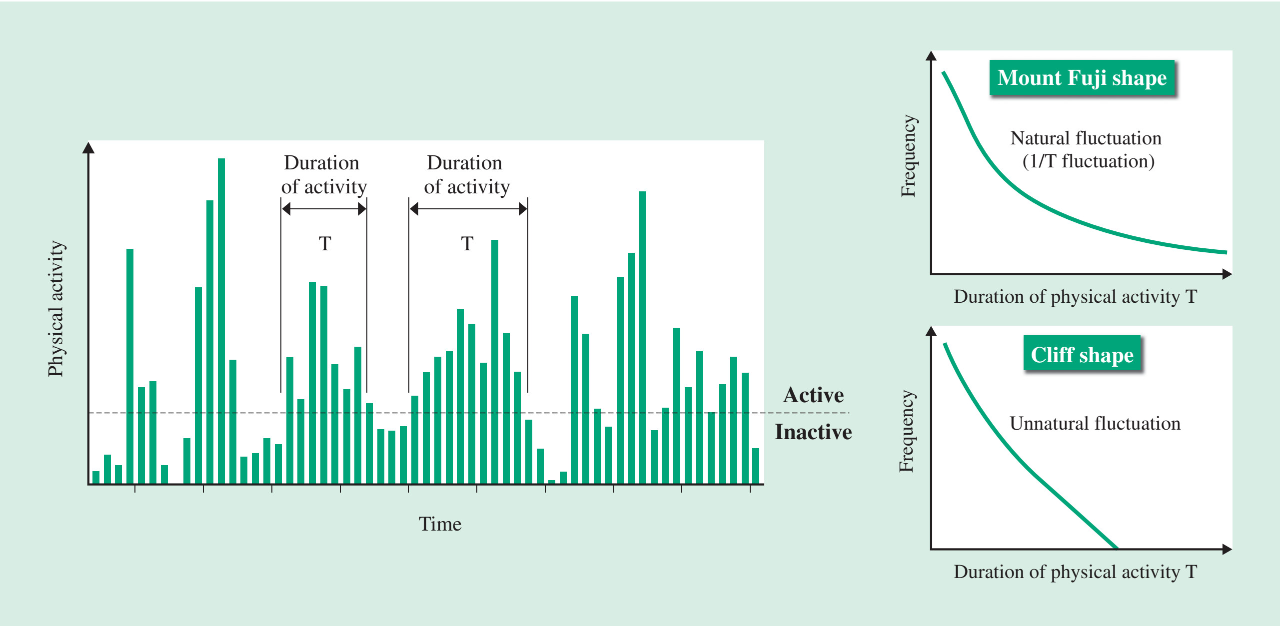

Fig. 2—Discovery of Distinctive Patterns of Physical Activity Associated with People's Happiness.
When physical activity is classified as either inactive or active and a frequency distribution obtained by counting the durations of activities classed as "active," groups with a high level of happiness are found to have a low degree of deviation from the 1/T rule (Mount-Fuji-shaped graph) and groups with a low level of happiness have a large deviation from the 1/T rule (cliff-shaped graph).

law, which states that a body will remain in uniform linear motion unless acted on by an external force.

When looking at the fluctuation data for individual groups, what is found is not a perfect match with the 1/T rule. Rather, some groups follow the rule comparatively closely while others diverge considerably. This 1/T fluctuation (the extent to which the data fits the 1/T rule) is adopted as a numerical indicator. When 1/T fluctuation is large, the frequency distribution of the activity duration T looks like Mount Fuji with a long tail. In contrast, the T frequency distribution becomes more cliff-like and the tail disappears when 1/T fluctuation is low. This corresponds to the second law of motion in the presence of a force.

The authors discovered that this 1/T fluctuation is strongly correlated with happiness(13). Sensors were attached to 468 employees from 10 departments across seven companies to collect approximately 5,000 person-days or roughly five billion points of acceleration data. The relationship between these results and happiness scores from questionnaires was then analyzed. The questionnaires used were from the Center for Epidemiologic Studies Depression Scale (CES-D)(14). The CES-D questionnaire asks respondents to give a ranking between 0 and 3 to questions such as "how often you've felt that you were happy during the past week?" It contains a balanced mix of questions relating to things that contribute to or detract from happiness, with the score being obtained by totaling the responses to 20 questions of this nature on things like concentration, enjoyment, desires, good sleep, conversation, appetite, depression, anxiety, loneliness, and sadness (such that $3 \times 20 = 60$ points corresponds to being most happy and zero points corresponds to being least happy). While the CES-D questionnaire was developed for self-assessment of depressive tendency, it was adopted for testing on the assumption that explaining the decline in happiness due to the depressive tendency would be a necessary prerequisite for constructing a measure for happiness.

The results found a high correlation between the above 1/T fluctuation indicator and the departmental mean values of the happiness scores from the 468 subjects (see Fig. 3). Because the likelihood of this result obtained by chance is less than one in one million, this alternative (chance) can be ruled out. In other words, it is possible to obtain regular ongoing quantitative measurements of happiness within an organization by attaching wearable sensors to people's chests.

Note that happiness and level of activity are completely different things. The level of activity in a sales job that entails a lot of walking around is typically much higher than in sedentary office work. Despite this, sales work is not invariably happier

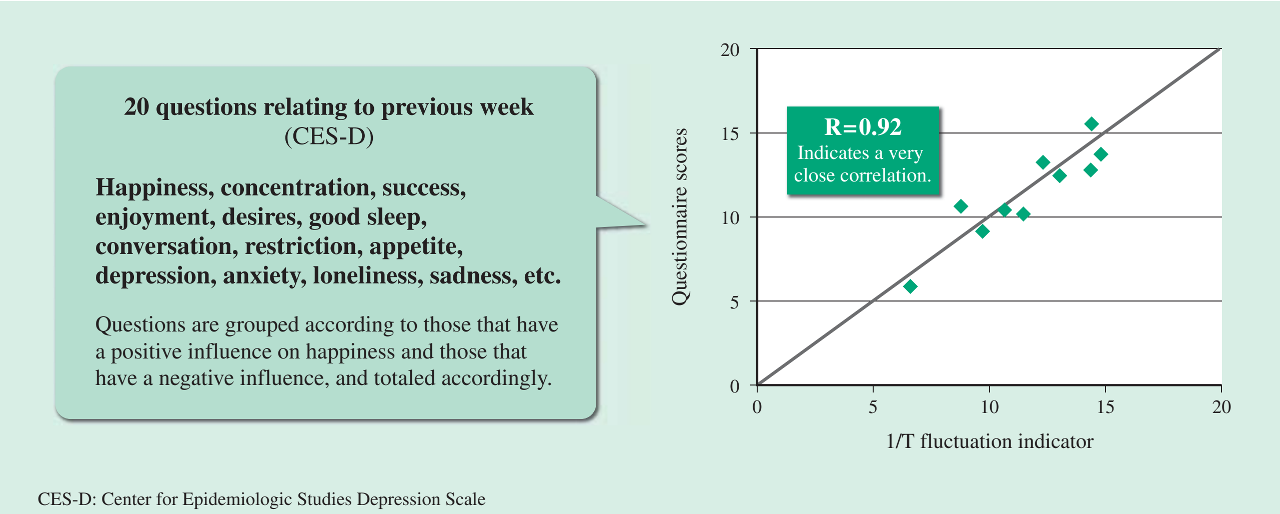

Fig. 3—Relationship between People's Physical Activity and Questionnaire Results.
The results of a questionnaire were compared with approximately 5,000 person-days or roughly five billion points of measurement data collected from 468 employees from 10 departments across seven companies.

than office work. Although people's level of physical activity varies depending on their job and position, this measure of happiness captures hidden features of physical activity that do not depend on such superficial factors as job and position.

One characteristic of 1/T fluctuation is that physical activity in a group has many components. Accordingly, groups that have a high level of happiness also have a high level of diversity in their body movements. Conversely, groups that have a low level of happiness also have a low level of diversity in their body movements. In other words, this technique is using the lens of physical activity to quantify whether or not there is diversity in group activities.

Happiness Influences Call Center Productivity

There are some people who think this way: As a subjective concept, happiness could be just an indication of self-satisfaction; if people are placed in a comfortable environment, they may lose the motivation to achieve; it should be true that it is when people feel threatened or anxious that they exert their power to the fullest. Nevertheless, the data indicates otherwise.

The authors conducted an experiment at a call center[15]. Specifically, this experiment involved having 215 subjects working at two different sites wear sensors over a 29-day period (providing a total of 6,235 person-days of acceleration measurements comprising roughly six billion data points), and then investigating the relationship between the 1/T fluctuation of physical activity and work productivity (as measured by the rate of successful sales). The call center engaged in cold calling potential customers to try to sell them a particular service.

The rate of daily orders differed by a factor of three depending on such things as the site or day. The main factor in this variation in results was found to be the 1/T fluctuation of physical activity (in other words, happiness) (see Fig. 4). Because many of the call center staff worked part time, the mix of people at work was different every day. The overall happiness of the staff as measured by the sensors varied between sites and from day to day. Furthermore, staff (days, sites) with above-average 1/T fluctuation had an order rate 34% higher than those with below-average 1/T fluctuation.

This demonstrates that the 1/T fluctuation of physical activity (happiness) that is associated with staff performing at a high level and achieving good results is not simply a matter of providing a relaxing, stress-free environment. In fact, these results confirm that the level of happiness in relaxing environments is not high. According to Mihaly Csikszentmihalyi, this is because such conditions are close to a state of boredom[16]. Achieving happiness and enjoyment requires challenging but achievable tasks that push the limits of the person attempting them. On the other hand, a level of challenge that is too high invokes anxiety and diminishes performance. It also reduces productivity. Happiness corresponds to the roof covering the valleys of boredom and anxiety and is a state of high productivity. The measurement of 1/T fluctuation is a valuable tool for staying on top of this roof.

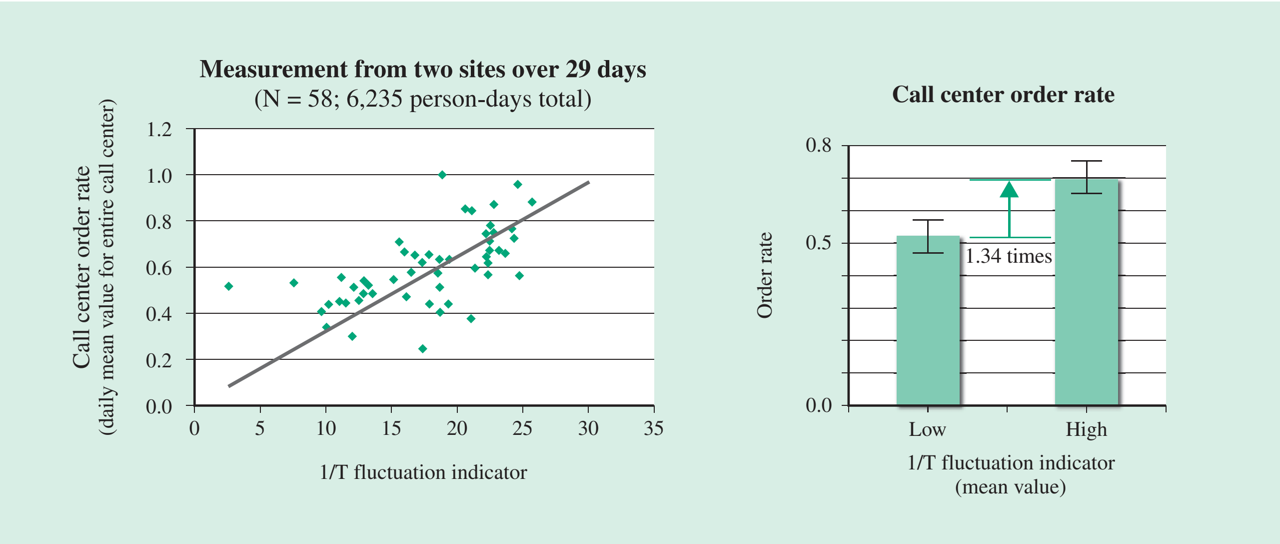

Fig. 4—Demonstration of Direct Link between 1/T Fluctuation of Physical Activity (Happiness) and Work Productivity at Call Center.
An experiment found a 34% higher order rate on days with above-average 1/T fluctuation compared to below-average days.

In the case of this call center, the thing that determined staff happiness turned out to be something quite unexpected: it was their level of physical activity during breaks. The staff room is a place to sit down and relax. The physical activity recorded by the sensors consisted largely of people chatting with other staff. On days when there was a high level of conversation among staff as a whole during breaks, the call center's overall level of happiness was high, as was the order rate.

The important point here is not that the order rate was high only for those staff whose level of physical activity (conversation) was high, but that the overall level of group happiness was higher and a better overall order rate was achieved on days when the group as a whole had a high level of physical activity. In other words, physical activity, happiness, and the level of orders all turned out to be collective phenomena. This means that, even in work that would be expected to depend on individual performance, staff were performing influenced by unconscious interaction with those around them.

Furthermore, the data also clearly indicates a way of invigorating conversation during breaks: have the supervisor speak to staff during work time. Appropriate communication with the supervisor during work times led to more conversation during breaks, which enhanced staff happiness and boosted the order rate. A sustained improvement in call center order rate of more than 20% was achieved when, prompted by this result, the call center utilized a cloud application that facilitated supervisors speaking to staff.

SHORTENING THE BUSINESS CYCLE

There is no reason to assume that the strong relationship between physical activity, happiness, and work productivity only applies at call centers. It has been reported that the contribution of happiness to performance is even greater in creative work[(1)]. Although lack of space prevents the inclusion of details in this article, the authors have demonstrated that the 1/T fluctuation of development team members two months after the start of a product development project is a leading indicator of sales five years later.

In the case of knowledge work, there is often a long time-lag before financial results emerge. In the case of product design, for example, it is not unusual for a year to pass before it is clear whether or not the product has been a success. In the case of business sales, orders are often determined by a year-long budgeting cycle. These time-lags are even longer in the case of research and development.

Because the people involved and other external circumstances change over time, it tends to be unclear which actions were instrumental to success. This is why existing management accounting and human resource systems fail in practice. Financial results on their own are inadequate as feedback for knowledge workers.

On the other hand, the use of 1/T fluctuation as a three-way indicator of physical activity, happiness, and work productivity enables the plan, do, check, and act (PDCA) cycle to be implemented in a very short timeframe. This can be incorporated into corporate systems.

Corporate Systems that Incorporate Happiness

Business is made up of many people and organizations. Nevertheless, there is a tendency to go no further than local optimization within the scope of individual responsibilities. On the other hand, attempting to consolidate the administration of all information and authority does not work either. This is because there is a lack of utilization of experience and other forms of workplace information that cannot be transformed into data. This is the biggest challenge facing the 21st century workplace.

However, by measuring happiness it is possible to build systems that overcome this challenge. Specifically, this involves treating business as a "system of systems" made up of a large number of people who play the role of sub-systems. The terminology includes "outcomes" (meaning overall results), "key performance indicators (KPIs)" as the measure of individual performance, and "evaluation functions" as the formulas used to calculate KPIs. It is possible to work toward system-wide optimization in a changing environment by incorporating factors that affect overall performance into the KPIs set for individuals, while also having people decide and act autonomously in accordance with their own KPIs.

There should be the best way to incorporate the factors that contribute to system-wide optimization into the KPIs of individuals. The baseball concept of sacrifice hits (such as bunts) provides a model for this. Although a player who makes a sacrifice hit gets out without reaching first base, that player still contributes to the team. If this sacrifice hit is included in the player's batting evaluation, then it can improve overall team performance. In baseball, sacrifice hits are excluded from the batting average calculation and are assessed on their own. Here, getting on base is called a "direct variable" and a sacrifice hit is called a "symbiotic variable."

In practice, the chain of influence from one person to another in an actual business is complex and identifying symbiotic variables is more difficult than it is in baseball. Hitachi's "H" artificial intelligence (an abbreviation of "Hitachi Online Learning Machine for Elastic Society") can automatically generate individual KPIs that include symbiotic variables and the evaluation functions used to calculate them from big data, and can also provide the rationale for them. In particular, by using the 1/T fluctuation indicator for all people involved as a leading indicator of business performance, it is possible to simplify the problem to a large degree by shortening the cycle time for action and results. The inputs to H are the outcome definitions and various operational data such as the activity data for each person. Based on this, H automatically generates a large number of hypotheses about the factors that influence outcomes (with a number of candidate variables ranging between one hundred and one million), narrows these down to a small number of important factors, and then generates the evaluation function(9).

By using the evaluation functions produced by H (which include symbiotic variables), it is possible to achieve system-wide optimization through the effect of these symbiotic variables while still enabling individuals to make their own decisions based on their own KPIs. That is, it is possible for corporate accounting, production, and human resource systems to maximize the happiness and productivity of everyone involved. By having H automatically update these evaluation functions using daily data, it is possible to work continually toward system-wide optimization in a changing environment by having KPIs adapt to the circumstances.

This has the potential to revolutionize a wide range of corporate activities (see Table 1).

Table 1. Applications for Measuring Happiness

The technique has applications in a wide range of businesses where organizational revitalization and productivity improvement, etc. are relevant.

Business	Objectives	Anticipated benefits
Research and development	• Evidence-based project management • Early assessment and action on objectives and organizational structure	• Accelerate innovation. • Improve return on investment.
Organization management (M&A, etc.)	• Management of organizational restructuring • Performance assessment and actions for leaders	• Successful restructuring • Improve employee satisfaction.
HR (promotions, evaluation)	• Organizational revitalization • Assessment and training of managers	• Improve employee satisfaction, reduce staff turnover. • Improve management capabilities.
Engineering and manufacturing	• Evidence-based engineering and manufacturing • Improve product quality (defects, accidents).	• Improve productivity of engineering and manufacturing, prevent delays. • Prevent major recalls, improve quality.
Sales and marketing	• Evidence-based sales management • Expedite training of sales and marketing staff.	• Increase sales revenue. • Improve customer engagement.
Services	• Motivate and improve productivity of staff. • Get new sites established quickly.	• Improve productivity, improve ability to acquire workers. • Get new sites established quickly.

HR: human resources M&A: mergers and acquisitions

Controlling Happiness

The controllable degrees of freedom for maximizing happiness are extensive. Controlling the air conditioners in buildings is one example. Instead of conventional air conditioning that maintains a constant temperature, using happiness measurements and artificial intelligence, it is possible to operate the air conditioning in a way that maximizes the overall happiness of the people in the building.

At the call center, it was possible to enhance overall happiness and productivity by controlling communication between staff. In that case, conversation during breaks was treated as a symbiotic variable for operators, and talking to staff while they are working in the right way was treated as a symbiotic variable for supervisors. By having a business system that included such symbiotic variables, the overall productivity of the call center was significantly improved by operators raising their KPIs, which included symbiotic variables as well as direct variables like their order rate.

Another example to be considered is improving healthy life expectancy while minimizing medical costs at community healthcare systems. In a case like this, the cycle time is too long to permit a data analysis of the relationship between policy changes and changes in the community's healthy life expectancy. However, the cycle can be shortened dramatically by treating 1/T fluctuation as an outcome, enabling the PDCA cycle to be worked through on a daily basis.

CONCLUSIONS

The 18th century philosopher, Jeremy Bentham, put forward the idea of "the greatest happiness of the greatest number," suggesting that the quantification of happiness could provide a benchmark for ethical decisions. Subsequent criticisms of Bentham, however, concluded that, ultimately, happiness is not something that can be measured. This technology has the potential to overturn this state of affairs.

In the past, many organizations have persisted with unilateral rules even in cases where flexible judgment based on the circumstances is called for. This is because establishing and then sticking to detailed unilateral rules and other processes have become the main way of managing groups. This approach has its origins in the scientific management methods proposed by Frederick W. Taylor in the early 20th century. However, as noted by Peter F. Drucker, scientific management lacks flexibility and does not adapt well to change(17). Management in the 21st century needs to set its sights beyond these limitations and equip itself with the flexibility to handle a variety of different situations.

The 20th century was characterized by people having to adjust to systems and rules. The future, in contrast, will see the level of individual happiness enhanced through artificial intelligence and the quantification of happiness, with systems and rules having to adjust to people. As a breakthrough in assessing the collective unconscious, the measurement of happiness has the potential to revolutionize not only people's lives but also management and consensus-building within companies, communities and nations, and even humanity as a whole, by providing a means of visualizing people's happiness.

The data presented in this article was obtained by the human big data / cloud services of Hitachi High-Technologies Corporation and is managed under a business-to-business service contract that includes ethical terms (including protection of personal information and information security) under the ethical standards of the Hitachi Group.

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Featured Articles

New Computing Paradigm for Analyzing Increasingly Complex Social Infrastructure Systems

—Ising Computer—

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OVERVIEW: The optimization of social infrastructure systems will be among the requirements of Hitachi's Social Innovation Business in the future, therefore, there will be a need to solve combinatorial optimization problems. Hitachi has devised a computing technology based on a new paradigm that is capable of solving combinatorial optimization problems efficiently using an Ising model, and has built a prototype 20,000-spin Ising chip using a 65-nm process. An Ising chip represents a combinatorial optimization problem by mapping it onto an Ising model based on the spin of magnetic materials, and solves the problem by taking advantage of the system's natural tendency to converge. This convergence is implemented using a CMOS circuit. In addition to demonstrating its ability to solve combinatorial optimization problems and operate at 100 MHz, the prototype chip consumes approximately 1,800 times less power to obtain the solution than required by a conventional Neumann-architecture computer.

INTRODUCTION

SOCIAL innovation will be essential to the ongoing progress of society and to providing a more comfortable way of life in the future. Achieving this will require a combination of advanced information technology (IT) and infrastructure technologies for building a prosperous society. As epitomized by the supercomputer, the focus in IT to date has been on performing large numbers of numerical calculations. However, achieving social innovation will require the optimization of social systems. Transportation systems, logistics systems, and electric power grids, for example, need to optimize vehicle movements, delivery routes, and power flows (see Table 1). Optimizing these social systems involves solving what are known as "combinatorial optimization problems." However, problems of this class are difficult to solve efficiently using conventional computing techniques. In response, to provide the computing techniques needed to achieve social innovation, Hitachi has developed a new concept in computing that can efficiently solve combinatorial optimization problems.

This article describes this new computing paradigm.

TABLE 1. Example Systems Essential to Social Innovation
Future social infrastructure system optimization will require the solution of combinatorial optimization problems to determine control parameters from information input from sensors and other sources.

System	Transportation	Logistics	Electric power grid
Objective	Reduce trip times.	Reduce delivery costs.	Reduce electric power generation and storage.
Input information	Traffic conditions Destination of each vehicle	Cost of using each route	Power generation Power use
Control parameters	Signals Vehicle movements	Delivery routes	Power flow routes
Combinatorial optimization problem	Maximum flow Shortest route	Traveling salesman	Maximum flow

COMBINATORIAL OPTIMIZATION PROBLEMS

A combinatorial optimization problem involves finding the combination of parameters that maximize (or minimize) a performance index under given conditions. This section uses the traveling salesman problem as an example and describes the difficulties associated with solving combinatorial optimization problems using existing computing techniques.

Example Combinatorial Optimization Problem

The traveling salesman problem is one of the most well-known of all combinatorial optimization problems. Given a list of cities and the distances between them, the problem is to find the shortest route that visits every city and returns to the point of departure. If the number of cities is N_c, then the number of routes visiting all cities is $(N_c - 1)!/2$. As the equation indicates, the number of possible routes increases explosively as N_c increases.

A characteristic of combinatorial optimization problems like this is that the number of candidate solutions increases explosively the greater the number of parameters that define the problem. It is anticipated that the number of parameters to be optimized for social infrastructure systems will increase in the future as the systems themselves become larger and the connections between them become more complex. This means that, for combinatorial optimization problems relevant to social innovation, the number of candidate solutions can be expected to increase explosively.

Methods for Solving Combinatorial Optimization Problems and Associated Difficulties

The solution of combinatorial optimization problems using existing computing techniques involves calculating the performance index for all parameter combinations and then selecting the combination that results in the minimum performance index [see Fig. 1(a)]. Accordingly, the number of combinations for n parameters will be 2^n. In a problem with 1,000 parameters, for example, the number of combinations is 2^{1000}, or approximately 10^{300}. Calculating performance indices for such a huge number of combinations is impossible in practice.

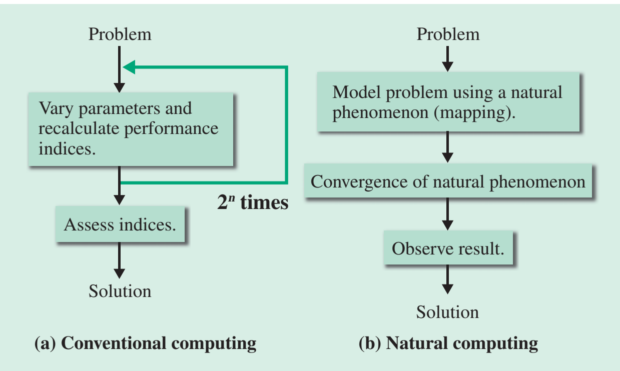


Fig. 1—Procedure for Solving Optimization Problems.
The practice using conventional computing has been to repeatedly calculate the performance index under all conditions and then assess the values obtained. Natural computing, in contrast, reduces the number of calculation iterations by taking advantage of the tendency for a natural system to converge.

What is actually done in situations like this is that, rather than calculating the performance indices for all combinations, an approximation algorithm is used to obtain a roughly optimal combination of parameters. Unfortunately, as the number of parameters increases, finding even an approximate solution becomes difficult. Furthermore, semiconductor miniaturization has enabled the computational methods used in the past to deal with larger problems by improving the performance of the central processing units (CPUs) used for the calculations. There has been talk in recent years that progress on semiconductor miniaturization has plateaued, and in practice there have been no further improvements in CPU clock speeds since the late 2000s. In other words, optimizing the larger and more complex systems of the future will require computing techniques that do not rely on the practices of the past.

NEW COMPUTING CONCEPT

Conventional computers break a problem down into a collection of programs (procedures) and solve the problem by executing these sequentially. As noted above, however, the difficulty with solving combinatorial optimization problems is the explosive growth in the number of procedures required for program execution. Accordingly, Hitachi has proposed adopting a different computing concept, namely "natural computing." This section describes natural computing and presents an example in the form of a computing technique that uses an Ising model.

Natural Computing

Fig. 1(b) shows a flow chart of a calculation that uses natural computing. Natural computing works by using a natural phenomenon to model the problem to be solved (mapping) and takes advantage of the convergence implicit in this natural phenomenon to converge on the solution to the problem. The problem can then be solved by observing this converged result. Table 2 lists examples of natural computing. Neurocomputing, which is based on the behavior of neurons in the brain, can increase the speed of recognition processing used in artificial intelligence. An Ising model, meanwhile, represents the behavior of magnetic spin in a magnetic material in terms

TABLE 2. Examples of Natural Computing

Techniques have been proposed for using natural phenomena for computing. These techniques can be used for tasks such as recognition or solving combinatorial optimization problems that have not been a focus of attention in the past.

	Neurochip	Superconductor Ising model	Technique described in this article
Natural phenomenon	Brain (neuron)	Spin of magnetic material (Ising model)	
Physical implementation	Semiconductor	Superconductor	Semiconductor
Application	Recognition	Optimization problems	
Year of publication	2014	2011	2015

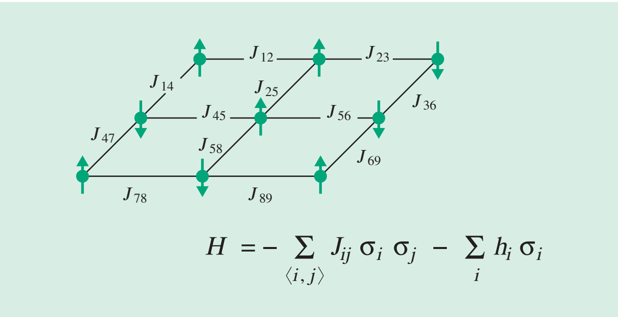


Fig. 2—Ising Model.

An Ising model represents the properties of ferromagnetic materials in terms of statistical mechanics. It consists of a lattice of points (spins), each of which can occupy one of two orientation states, and reaches stability when the energy H is at a minimum, taking account of interactions between adjacent points in the lattice.

of statistical mechanics and has been proposed as a suitable technique for solving combinatorial optimization problems.

Ising Model and Associated Computing Technique

Fig. 2 shows an Ising model. The properties of a magnetic material are determined by magnetic spins, which can be oriented up or down. An Ising model is expressed in terms of the individual spin states (σ_i), the interaction coefficients (J_{ij}) that represent the strength of the interactions between different pairs of spin states, and the external magnetic coefficients (h_i) that represent the strength of the external magnetic field. The figure also includes the equation for the energy (H) of the Ising model. One property of an Ising model is that the spins shift to the states that minimize this energy, ultimately leaving the model in this minimum state. If a combinatorial optimization problem is mapped onto an Ising model in such a way that its performance index corresponds to the model's energy, and if the Ising model is allowed to converge so that the spin states adopt the minimum-energy configuration, this is equivalent to obtaining the combination of parameters that minimizes the performance index of the original optimization problem.

As shown in Table 2, a computing technique has already been proposed that uses superconductors to replicate an Ising model.

CMOS ISING COMPUTING

Hitachi has proposed using a complementary metal oxide semiconductor (CMOS) circuit to simulate this Ising model. The benefits of using a CMOS circuit are simpler manufacturing, scalability, and ease of use. This section describes how CMOS can be used for Ising computing.

Using CMOS to Simulate an Ising Model

Hitachi has proposed a way of using CMOS to simulate an Ising model. Because an Ising model requires that spin states be represented as binary values, these states are stored in semiconductor static random access memory (SRAM). The interaction coefficients that represent the strength of the interactions between pairs of spin states and the external magnetic coefficients that represent the strength of the external magnetic field are also stored in SRAM. Similarly, the interactions that cause the spin values to change are replicated through the operation of digital circuits.

To achieve this, each spin is represented by the circuit shown in Fig. 3. This includes the memory circuits that store the spin states, interaction coefficients, and external magnetic field coefficients, and the digital circuit that calculates the interactions.

To calculate the interactions, the values of adjacent spin states are provided as inputs to each spin circuit. The following procedure is then used to update the spin state values. First, the spin values are read and input to adjacent spin circuits. Simultaneously, the interaction coefficients are also read. These are used to calculate new spin values, which are then updated in memory. This updating process is performed concurrently for all isolated spins. What this means is that any increase in the number of spins in an Ising model is matched by a change in the number of concurrently updated spins, therefore the total number of spins has little effect on the total time taken for spin state updating (the computing time taken for the Ising model to converge).

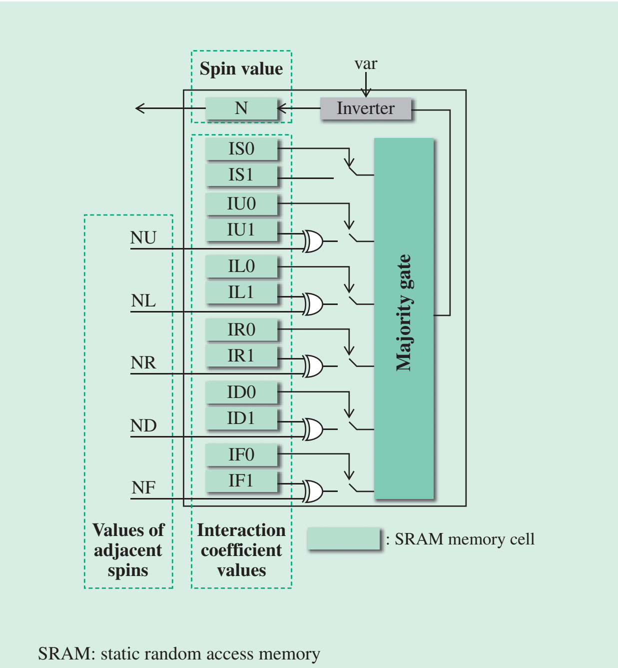


Fig. 3—Spin Circuit for Single Spin.
The circuit consists of SRAM memory cells that hold the spin values and interaction coefficients, and a majority gate that computes the interactions. The values of adjacent spins are input from their respective circuits.

Actual spin value updating is performed by the circuit in Fig. 3 in accordance with the following rule:

New spin value = +1 (if $a > b$)
−1 (if $a < b$)
+/−1 (if $a = b$)

Here, a is the number of cases in which (adjacent spin value, interaction coefficient) is (+1, +1) or (−1, −1) and b is the number of cases in which it is (+1, −1) or (−1, +1).

As the interaction process acts so as to cause spins to change to the same orientation as adjacent spins if they have a positive interaction coefficient, and to the opposite orientation if they have a negative interaction coefficient, the new spin value is determined by which of these is in the majority. This is determined by determining which influence from adjacent spins predominates (is in the majority). In the actual circuit, the influence of each spin is converted to a current and the interaction is replicated by determining which type of current is in the majority.

CMOS Annealing

The interaction process described above causes the energy of the Ising model to fall, following an energy profile like that shown in Fig. 4. However, because the energy profile includes peaks and valleys (as shown in the figure), this interaction process operating on its own has the potential to leave the model trapped in a local minimum in a region that is not the overall minimum for the system.

To escape such local minima, the spin states are randomly perturbed. In practice, this means injecting a random string into the var signal in the Fig. 3 spin circuit. If the value of the random string is “1,” the updated spin value is inverted by an inverter circuit included as part of the spin circuit, causing the system to randomly switch to an unrelated state as indicated by the dotted line in Fig. 4. Collectively, these two processes are called CMOS annealing. By using them, it is possible to identify the state with the lowest energy that can be found.

In practice, this use of random numbers means that the solution obtained is not necessarily the optimal one. However, when the computing technique is used for the optimization of social infrastructure systems, it is likely that it will not matter if the results obtained are not always optimal. When determining delivery routes, for example, it is unlikely to matter for the purposes of system optimization if the total route is slightly longer than it might have been. In situations where this computing technique might be deployed, it is possible to anticipate applications where the provision of a theoretical guarantee that it will produce solutions with 99% or better accuracy, 90% or more of the time, for example, will mean that these solutions can be relied on to not cause any problems for the system.

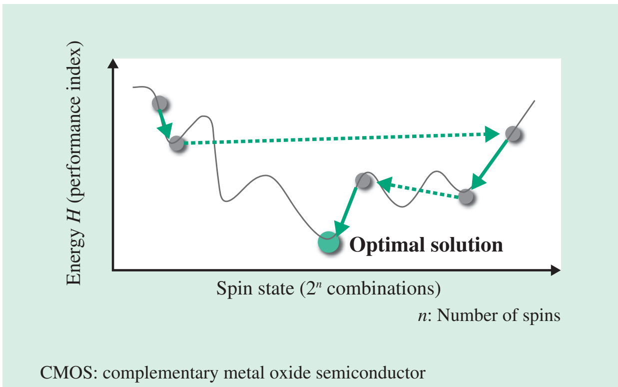
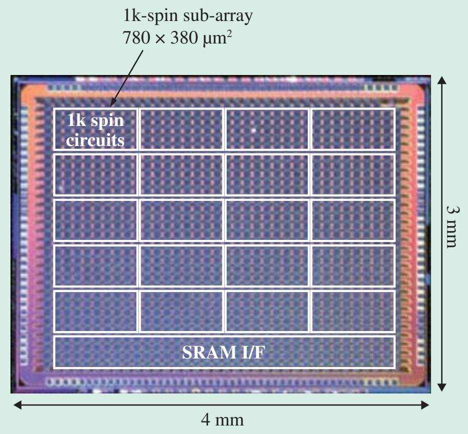


Fig. 4—Ising Model Energy Profile and CMOS Annealing.
In Ising computing, although the energy falls in accordance with the energy profile due to the interactions between spins (solid arrow), there is a potential for it to get trapped at a local minimum. This can be prevented by inputting random numbers to deliberately invert spin values (dotted arrow). Called CMOS annealing, this operation obtains a solution with low energy.



I/F: interface

Fig. 5—Ising Chip Photograph.
The chip has 20,000 spin circuits in a 3-mm × 4-mm = 12-mm² area.

PROTOTYPE COMPUTER

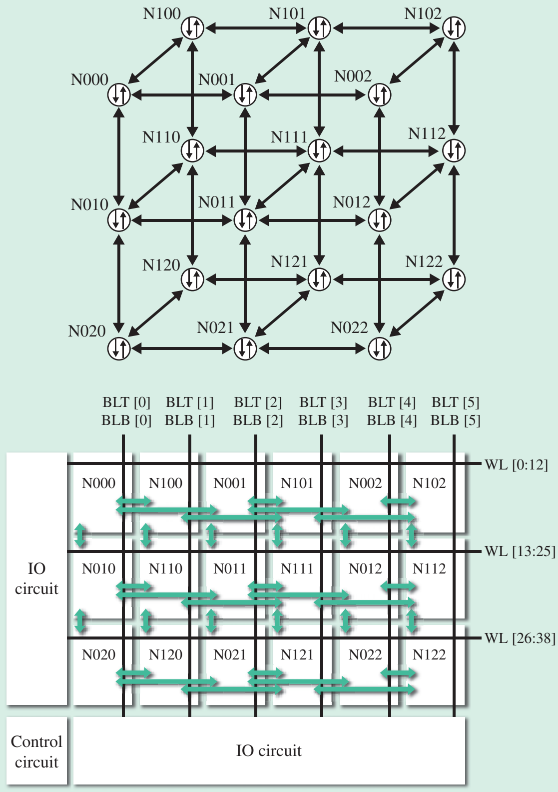
A prototype Ising chip was manufactured using a 65-nm CMOS process to test the proposed Ising computing technique. A prototype computer was then built with this Ising chip and its ability to solve optimization problems was demonstrated. This section describes the prototype computer and the results of its use to solve optimization problems.

Ising Chip

The prototype Ising chip was fabricated using a 65-nm semiconductor CMOS process. Fig. 5 shows a photograph of the chip. The 3-mm × 4-mm chip can hold 20,000 spin circuits, each occupying an area of 11.27 μm × 23.94 μm ≈ 270 μm². The interface circuit used for reading and writing the spin states and interaction coefficients operates at 100 MHz, as does the interaction process for updating spin values.

The Ising chip implements a three-dimensional Ising model consisting of two layers of two-dimensional lattice, as shown in the upper diagram in Fig. 6. The lower diagram shows how this three-dimensional Ising model is built using a two-dimensional memory layout. Semiconductor chips achieve a high level of integration by using a two-dimensional layout, and the prototype Ising chip also takes advantage of this to achieve a high level of integration, meaning that it can implement a large number of spin circuits.

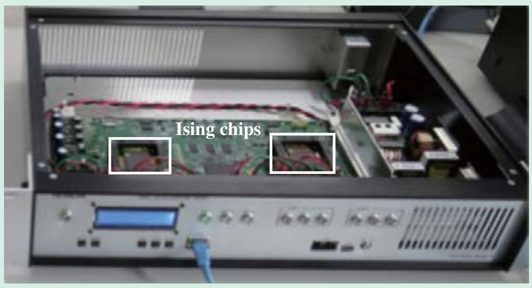
In this configuration, each spin circuit is connected to five others (left, right, front, and back and either above or below). To prevent connected spin circuits



IO: input/output

Fig. 6—Topology of Ising Model on Chip and Corresponding Memory Layout.
A high level of scalability is achieved by implementing a three-dimensional Ising model consisting of multiple two-dimensional Ising model layers on two-dimensional semiconductor memory.

from updating at the same time, only half of all spin circuits can be updated at each step. In practice, the design only updates one-eighth of the spin circuits at



PC: personal computer LAN: local area network

Fig. 7—Prototype Ising Computer.
The photograph shows an Ising node with two Ising chips. The prototype Ising computer is connected to a server or PC via a LAN cable and can be used to solve combinatorial optimization problems.

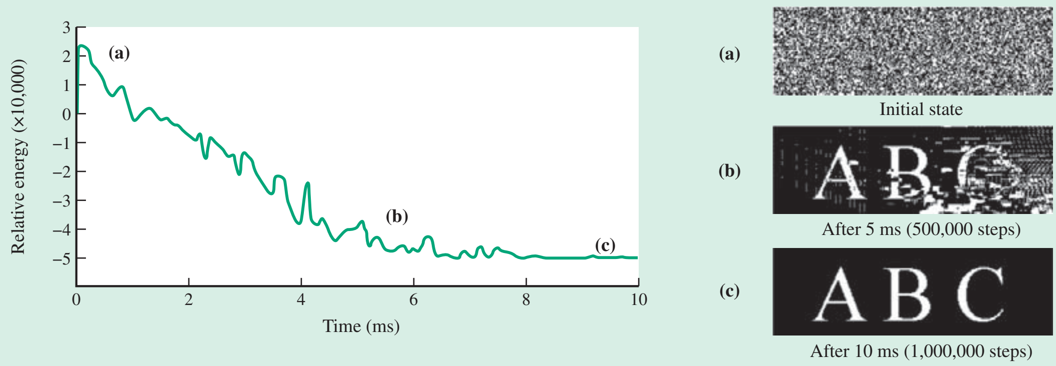


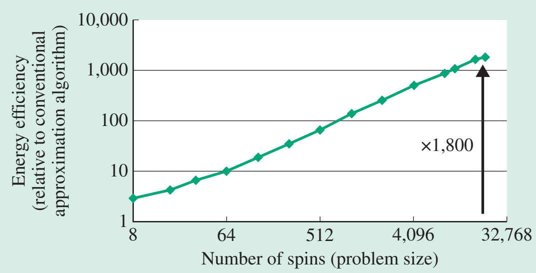
Fig. 8—Changes in Energy and Spin States while Solving a Combinatorial Optimization Problem.
The graph on the left shows how energy changes over the course of solving a maximum cut problem, a form of combinatorial optimization problem. The images on the right show the changes in spin states. The results indicate that the solution to the combinatorial optimization problem was obtained in about 10 ms.

each step in order to minimize the power consumed when interactions are performed concurrently.

Prototype Ising Computer

Fig. 7 shows a prototype Ising computer fitted with two Ising chips. The prototype computer can be accessed from a personal computer or server via a local area network (LAN) to input optimization problems and obtain the solutions.

Fig. 8 shows the results of using the Ising chip to solve a form of combinatorial optimization problem called the maximum cut problem. The graph on the left shows how the energy of the Ising model changes over the course of solving the problem. The energy falls over time and reaches a minimum after about 10 ms.



CPU: central processing unit

Fig. 9—Energy Efficiency of Solving Randomly Generated Maximum Cut Problem.
The graph shows the relative energy efficiency of the calculation compared to an approximation algorithm executing on a general-purpose CPU. The energy efficiency improves as the size (number of spins) of the problem increases, with the new technique being approximately 1,800 times more efficient for a 20,000-spin problem.

The two-color images on the right show the changes in spin states as the problem was being solved. White dots represent spin up and black dots represent spin down. The problem used for this demonstration was selected such that the spin states would spell out the letters “ABC” when the optimal solution was found. The spin state images show the spin states starting out randomly, with no regularity in the distribution of white and black dots. After 5 ms, the energy of the Ising model has fallen and the letters have begun to appear amid a certain amount of noise. As indicated by the presence of noise, this state represents a local minimum. The energy continues to fall as further CMOS annealing is performed, resulting in the letters appearing noise-free after about 10 ms. This state represents the energy minimum and indicates that the optimal solution to the maximum cut problem has been obtained.

While the optimal solution was obtained in this example, this will not happen in all cases. Nevertheless, it demonstrates that the operation of the chip can solve combinatorial optimization problems by reducing the energy.

Fig. 9 shows a comparison of the energies required to solve a randomly generated maximum cut problem using this technique and using conventional computing. The horizontal axis represents the number of spins in the Ising model. The energy use for conventional computing was measured by running the SG3 approximation algorithm (which has been optimized for solving maximum cut problems) on a general-purpose CPU. The same problems were solved using both techniques and a comparison made of the energies consumed in obtaining a solution to an

TABLE 3. Comparison with Existing Ising Computers
The new technique is significant in engineering terms because it is suitable for real-world applications, being superior to an existing Ising computer that uses superconductors in terms of things like ease of use and scalability.

	New technique	Existing technique
Approach	Ising computing	
	Semiconductor (CMOS)	Superconductor
Operating temperature	Room temperature	20 mK
Power consumption	0.05 W	15,000 W (including cooling)
Scalability (number of spins)	20,480 (65 nm) Can be scaled up by using higher level of miniaturization or multiple chips.	512
Computation time	Milliseconds	Milliseconds (fast in principle)

equivalent level of accuracy in each case. Because the SG3 approximation algorithm used for the comparison has been optimized for maximum cut problems that use Ising models, there was no significant difference between the times taken by the two techniques for a problem with 20,000 spins. The amount of energy consumed in solving a 20,000-spin problem, on the other hand, was approximately 1,800 times less using the new technique.

CONCLUSIONS

Table 3 shows a comparison with previous Ising computers. Use of a CMOS semiconductor circuit means the computer can operate at room temperature. This means very little power is consumed for cooling. The number of spins is an important parameter because it determines the size of problems that can be solved. The prototype computer has approximately 20,000 spin circuits. In the future, it will be possible to replicate large Ising models by using higher levels of semiconductor process miniaturization. Furthermore, because the current system uses digital values to calculate spin interactions, it is easy to link a number of chips together and expand the size by using multiple chips.

Although it is anticipated that this use of digital circuits will result in lower solution accuracy than can be achieved by previous systems based on superconductors, it is adequate for use in the optimization of actual social infrastructure systems because it is able to solve problems in practice. Moreover, the approach described here of using a semiconductor is significant in engineering terms for reasons that include ease-of-use and scalability.

This article has described how the prototype Ising computer successfully solved a maximum cut problem, which is a form of combinatorial optimization problem. Because it is known that this problem can be translated mathematically into other combinatorial optimization problems, this indicates that the technique has the potential to be used in actual system optimization. Furthermore, energy measurements demonstrated that the technique can reduce consumption by three or more orders of magnitude compared to conventional computing techniques, making it suitable for use in future complex system optimizations.

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Special Article

Development of Holography Electron Microscope with Atomic Resolution

—Triumph over Numerous Difficulties—

Hiroyuki Shinada, Ph.D.

The development of an atomic-resolution holography electron microscope that began in earnest in March 2010 has now been completed with the achievement of world-leading resolution. This article describes the background leading up to the proposal for the microscope's development, the progress of that development with support from the FIRST Program, the features of the instrument, and its future applications. Beset, at first, by a series of unexpected misfortunes and setbacks that included the death by illness of the engineer leading the development shortly after the work commenced, the Great East Japan Earthquake, and the death of Dr. Tonomura, the lead researcher and originator of the project proposal, the development then had to overcome technical difficulties associated with high voltages before it finally succeeded in achieving a world-leading resolution of 43 pm in December 2014. In the future, Hitachi aims to use the microscope to accelerate the development of new functional materials through open innovation.

INTRODUCTION

THE transmission electron microscope was invented in Germany in 1932. It works by directing a beam of electrons through a specimen and then using a lens to enlarge the image formed by their passage. In Japan, development and research into its applications began in 1939, and numerous companies around the world have competed to develop the instruments since Hitachi developed its own first transmission electron microscope, the HU-1, in 1941. Hitachi supplied the first commercial model produced in Japan, the HU-2, to Nagoya Imperial University (as it was then known) in 1942(1). A transmission electron microscope exhibited by Hitachi at the 1958 World's Fair in Brussels won a grand prize(2), and since then Japanese instruments, including those made by Hitachi, have competed with the world's best(3).

Subsequently, the scanning electron microscope (SEM), which works by scanning a focused electron beam over the surface of the specimen, was successfully commercialized in 1965. The electron microscopes of that time used thermo electron guns, which are based on the thermionic emission of electrons by heating tungsten. Although the field emission effect (whereby electrons are emitted via the tunneling effect by applying a strong electric field to a sharp metal tip) was a known source for obtaining the electrons used by these microscopes, it had not been adopted in practice because it required extreme high vacuum, making it difficult to use in practice. With assistance from Professor Albert V. Crewe of the University of Chicago, Hitachi successfully implemented a practical electron source, and an electron gun to use it, and incorporated it into an SEM that was released on the market in 1972. From 1984 onwards, this technology became part of a major business dealing with critical dimension-scanning electron microscopes (CD-SEMs) specifically designed for measuring semiconductor patterns, a product category in which Hitachi continues to have the leading share of the global market(4).

Returning to the subject of transmission electron microscopes, since increasing the energy of the electron beam increases its ability to pass through specimens, the 100-keV energy of early instruments had increased ten-fold to 1 MeV(5), (6) by 1966 to enable the observation of thicker specimens, with the subsequent development of larger models up to 3 MeV(7), (8). As the history of the electron microscope is a long one that has been well documented elsewhere, this article will now move on to the subject of holography electron microscopes.

DR. TONOMURA AND HOLOGRAPHY ELECTRON MICROSCOPY

Early Years of Holography Electron Microscopy

To many people, the term "holography" will bring to mind the anti-counterfeiting holograms incorporated into credit cards or banknotes. However, the

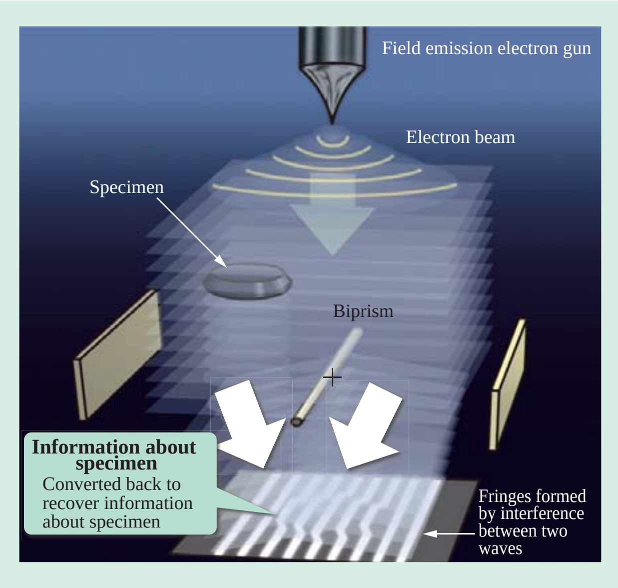

Fig. 1—Principle of Holography Electron Microscope.
Information about the electromagnetic fields in the specimen is obtained from interference fringes formed by field emission electrons emitted with high brightness and coherence from the metal tip.

technology was first invented in 1948 by Dennis Gabor as a way of improving the resolution of electron microscopes(9). The technology was not practically used at the time because the thermo electron guns used back then could only produce electron beams with low brightness and poor coherence. Subsequently, holograms (photographs containing three-dimensional information recorded using the holographic technique) like those of the present day that are able to be viewed under white light became possible following the invention and rise to prominence of the laser in 1960. During this time, research into holography for electron microscopes was making steady progress, with Dr. Akira Tonomura of Hitachi becoming involved in research in this field around 1968. Achieving electron holography in practice requires an electron beam with high brightness, a small source, and high coherence. What made this possible was the successful implementation by Hitachi in 1972 of the field emission electron gun referred to above. While this electron gun immediately entered widespread use thanks to the significant improvement it provided in SEM resolution, it was not adopted on transmission electron microscopes at the same time. Noting that field emission electrons exhibit a high degree of coherence, Dr. Tonomura developed the first practical holography electron microscope in 1978 by fitting a field emission electron gun to a transmission electron microscope(10), (11).

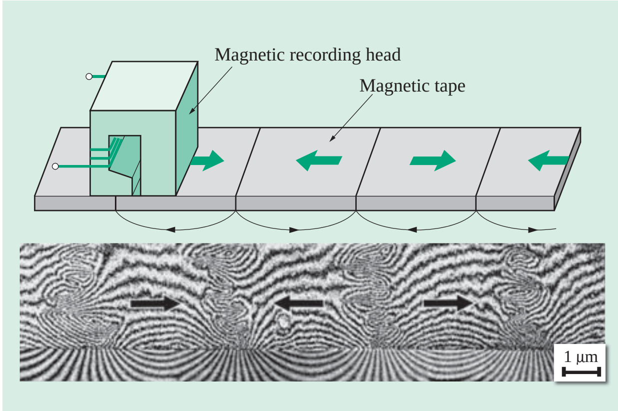

Fig. 2—Magnetic Fields of Recording on Magnetic Tape.
It provides clear images of the magnetization inside the tape and the magnetic fields outside the tape.

Electron Holography

This section explains the principles behind electron holography and describes the key work done by Dr. Tonomura and his team.

Part of the electron beam produced by the field emission electron gun is directed through the specimen, with a positively charged conductive filament (diameter: 1 µm or less) called a biprism inserted in the center of the downstream path. The phase of the electron beam is changed by its passage through the specimen. This beam then meets the other half of the electron beam that has traveled through vacuum (bypassing the specimen) at a detector (fluorescent plate or image sensor) where the beams overlap to form interference fringes. In the absence of a specimen, these interference fringes form a uniform pattern. When a specimen is present, on the other hand, the fringes change in ways that carry information about the specimen due to the phase change described above. This specimen information (such as its thickness or information about electrical and magnetic fields) can then be recovered by shining laser light on to the interference fringes (the hologram). In recent years it has become possible to digitize the image and reconstruct it using a computer (see Fig. 1).

Electron holography and the various methods associated with it have enabled such achievements as observing the magnetic fields of recordings on magnetic tape(12) (see Fig. 2), verifying the Aharonov–Bohm effect that experimentally confirms the presence of vector potentials(13) (see Fig. 3), and observing a quantum of magnetic flux (minimum unit of magnetic flux, approximately 2.0×10^{-15} Wb)

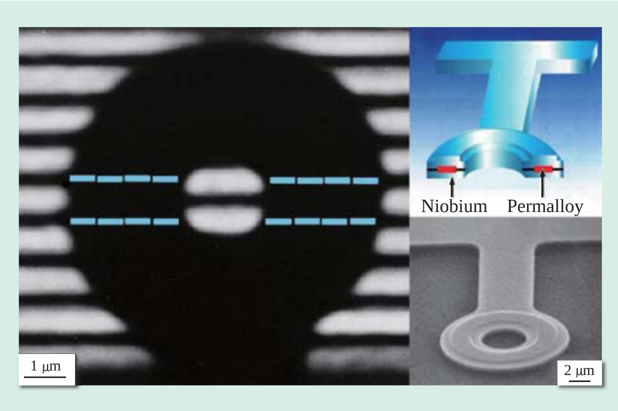

Fig. 3—Experimental Confirmation of Aharonov–Bohm Effect.
Permalloy, a ferromagnetic material, was formed into a donut shape and surrounded with niobium, then the temperature was lowered so that the niobium became superconducting, preventing the magnetic field from leaking out of the permalloy into the surrounding space. However, the electron beam interference fringes (phase) are shifted both inside and outside the donut. This occurs because the vector potential (a form of magnetic potential) changes the phase of the electrons, thereby providing experimental confirmation of the Aharonov–Bohm Effect (whereby charged particles such as electrons are influenced by the magnetic potential in space where there is no electromagnetic field).

leaking from superconducting niobium[14, 15]. In the case of the electron-beam version of the double-slit experiment[16], the technique makes it possible to observe how the interference fringes produced by the electron beam after it passes through the two slits form progressively as the cumulative number of electrons increases, starting out as just individual dots (particles) when the number of electrons is still small (see Fig. 4). This experiment was included in “The Ten Most Beautiful Experiments in Science”[17] for the way it gives an intuitive sense of the wave-particle duality of electrons, and is referred to in numerous physics textbooks both in Japan and overseas.

Development of Ultra-high-voltage Holography Electron Microscope

In 2000, Hitachi and The University of Tokyo jointly developed the world’s first 1-MV ultra-high-voltage holography electron microscope, which was capable of measuring electromagnetic fields in microscopic regions with a point resolution of 120 pm[18]. The development was part of the High-resolution Imaging of Phase and Amplitude of Electron Waves project, a Strategic Basic Research Program of the Japan Science and Technology Corporation (since renamed the Japan Science and Technology Agency). The work made a major contribution to elucidating the mechanism of high-temperature oxide superconductors by providing a direct view of magnetic flux in the superconductors. This took advantage of the enhanced ability of ultra-high-voltage electron microscopes to pass a beam through specimens. It also enabled the dynamic observation of fluxon motion that occurs when the magnetic field is varied and which are influenced by crystal defects[19].

DEVELOPMENT OF HOLOGRAPHY ELECTRON MICROSCOPE WITH ATOMIC RESOLUTION

After building the 1-MV holography electron microscope, Dr. Tonomura came up with an idea for the ultimate holography electron microscope. This was in response to the recent development of viable correctors (described below) for the spherical aberrations present in electron microscope lenses[20], a technology with the potential to dramatically

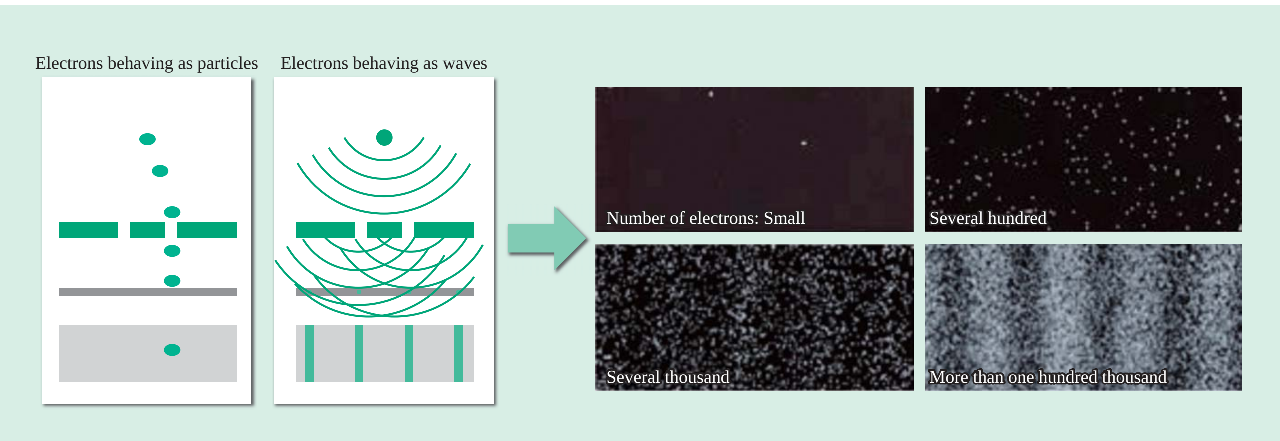

Fig. 4—Electron Double-slit Experiment.
While individual electrons are observed as particles, in large numbers they form the interference fringes characteristic of waves.

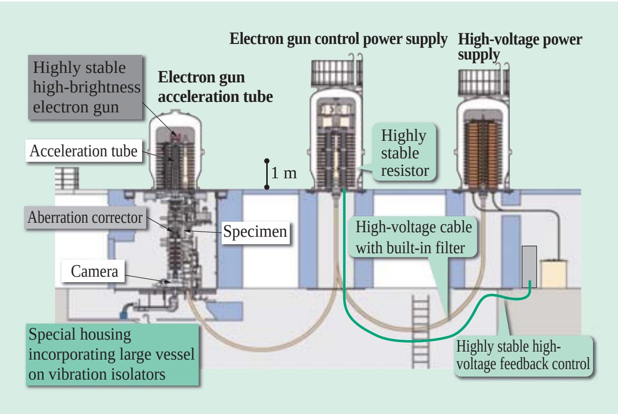

Fig. 5—Overview of Atomic-resolution Holography Electron Microscope.
The 1.2-MV ultra-high-voltage electron microscope has a three-tank design in which the high-voltage power supply is located separate from the electron microscope itself to ensure a high degree of stability. The tanks are connected by high-voltage cables.

Dr. Akira Tonomura (left) and Isao Matsui (right)

improve the resolution of ultra-high-voltage electron microscopes. However, getting the best performance out of an aberration corrector required improving the stability of the electron microscope unit by a factor of more than two. No group in the world had ever previously grappled with such a difficult problem using electron microscopes that were so large in size and worked with such high voltages. Dr. Tonomura decided to take on this challenge of building a holography electron microscope with atomic-scale resolution that would be able to observe magnetic fields at scales in the order of tens of picometers.

At this point it is essential to mention Isao Matsui, the engineer who worked in tandem with Dr. Tonomura on the development of the ultra-high-voltage holography electron microscope. Mr. Matsui, who led the development of Hitachi's ultra-high-voltage electron microscopes and, more recently, the 1-MV holography electron microscope, was a major participant in the development of these instruments. Dr. Tonomura and Mr. Matsui started out in pursuit of this dream in 2003. Their performance targets were resolution in the 40-pm range (the best resolution possible at the time was in the 70-pm range), the ability to use electron holography to detect differences in electron phase equal to one one-thousandth of the wavelength, and the ability to measure electromagnetic fields in three dimensions.

Four Major Obstacles to Overcome

The atomic-resolution holography electron microscope consists of three high-voltage tanks, with the electron microscope itself mounted on a vessel on vibration isolators (Fig. 5). The 1.2-MV high-voltage generator tank is on the right, the electron gun power supply that generates the control signals for the electron gun is in the middle, and the tank on the left contains the electron gun and the acceleration tube that accelerates the electron beam up to 1.2 MeV and is made up of layers of electrodes and insulators. The electron gun and acceleration tube are maintained in a state of extreme high vacuum with a pressure in the 10^{-9}-Pa range or less. Because these components are at a high negative potential (–1.2 MV), they would discharge if exposed to air. For this reason, these components are all housed in a tank containing sulfur hexafluoride (SF_6) gas, a discharge suppressant, at a pressure of four atmospheres. Because the high-voltage power supply generates acoustic and electrical noise, it is located away from the electron microscope and connected via a high-voltage cable. To prevent external vibrations from reaching the electron microscope, it is mounted on a cylindrical vessel on vibration isolators that is supported by dampers on four corners. The basic design is largely the same as that of the 1-MV ultra-high-voltage holography electron microscope completed in 2000[18]. However, there remained four major obstacles to overcome in order to achieve the performance targets set for the atomic-resolution holography electron microscope. The components associated with each of these challenges are highlighted in Fig. 5. This is explained in the following sections.

World's First Use of Spherical Aberration Corrector in Ultra-high-voltage Electron Microscope

To provide an enlarged image of the structure of a specimen, optical microscopes use a combination of convex and concave lenses to eliminate focal blur by correcting for spherical aberrations in the lenses. Because the electron lenses used in electron microscopes have for a long time not been able to function as concave lenses, spherical aberrations have been an obstacle in the way of improving resolution. While a practical system for correcting spherical aberration was developed in 1995[20], the electron microscope in which this spherical aberration corrector is used must be very stable for it to perform well. As a result, the system had not been successfully deployed in large ultra-high-voltage electron microscopes. In response, Hitachi developed the techniques described in the following three sections to make significant improvements in instrument stability, becoming the first in the world to successfully incorporate a spherical aberration corrector into an ultra-high-voltage electron microscope.

1.2-MeV Electron Beam with Reduced Energy Dispersion

Focal blur will occur regardless of the presence of a spherical aberration corrector if the dispersion in the energy of the electron beam is high. This makes it essential that the dispersion used to accelerate the electron beam be extremely stable. A calculation estimated that achieving the target resolution with the high-energy (1.2 MeV) electron beam would require that its dispersion be reduced to 0.54 eV. To improve the stability of the voltage used to accelerate the electron beam, Hitachi developed a number of components, including resistors with low noise and an electrical resistance that does not change significantly with temperature, a high-voltage power supply cable with a built-in noise filter, and a highly stable high-voltage feedback control circuit. These were used to develop a 1.2-MV ultra-high-voltage power supply system with stability of 3×10^{-7}, exceeding that of the previous microscope by about 70%.

Electron Gun Able to Produce Stable Electron Beam for Long Periods of Time

On conventional field emission electron guns like the electron gun in the 1-MV ultra-high-voltage electron microscope, the current of emitted electrons starts to fall immediately after electron emission is initiated by applying an extracting voltage to detach electrons. As a result, the extracting voltage needs to be recalibrated once or twice a day during use. Furthermore, because the trajectory of the electron beam shifts by a small amount each time the extracting voltage is recalibrated, it is not easy to keep the spherical aberration corrector operating with a perfectly aligned beam. Accordingly, to maintain optimal performance without having to recalibrate the spherical aberration corrector settings midway through a day's operation, Hitachi recognized the need for a field emission electron gun that could emit a stable electron beam for 10 or more hours at a time without calibration. While the Schottky-type electron gun[21], which uses an electric field to emit electrons from a heated emitter, is very stable, it is not suitable for holography electron microscopes because its energy dispersion is higher than for field emission electrons. This prompted Hitachi to set out to achieve high stability with an electron gun that emits electrons using only an electric field, without having to be heated. This requires an extremely high level of vacuum (3×10^{-10} Pa) at the location in the electron gun where electrons are emitted, approximately 100 times what was possible with previous instruments. Accordingly, they set about developing an electron gun that was able to work in this extreme high vacuum.

Development of Equipment Technology to Eliminate Factors that Degrade Resolution

Making atomic-scale observations requires that external interference with the electron beam or specimen, such as vibration, sound, or magnetic fields, is kept to an absolute minimum. To achieve this, Hitachi built a special reinforced building designed specifically to house the electron microscope, including walls lined with acoustic absorbent material and measures to minimize changes in ambient temperature. The targets were a high degree of sound insulation and low acoustic noise (20 dB or less above 200 Hz), reduced floor vibration (7.2×10^{-4} cm/s^2 at 100 Hz), and temperature variability in the vicinity of the microscope (ambient temperature) of ±2°C/8 h. To minimize magnetic fields, the area around the electron microscope was enclosed in permalloy to provide magnetic shielding.

Proposal and Adoption by FIRST Program

To achieve Dr. Tonomura's dream of a holography electron microscope with atomic resolution, it was first necessary to make solid progress on developing the technologies for overcoming the four main obstacles. In fact, the technologies were developed through participation in the Development of Elementary Techniques for Electron Microscope in Next Generation project, an experimental science and technology research project sponsored by the Ministry of Education, Culture, Sports, Science and Technology that ran from 2006 to 2008. Specifically, this included an ultra-precise reference voltage source, a high-voltage cable with built-in noise filter, a highly stable low-noise resistor module, and a high-resolution crystal lattice image evaluation technique. In the case of the high-resolution crystal lattice image evaluation technique[22] in particular, Dr. Tonomura's team succeeded in setting a new record of 25.9 pm for the smallest crystal lattice spacing ever observed (beating the old record of 49.8 pm) by minimizing external noise (such as vibration or electromagnetic fields), which degrades electron microscope resolution, and by using the dark field method whereby imaging only includes the high-order waves scattered by the crystal lattice. Most of the technologies developed through this work are now featured in the latest electron microscopes. However this also included one factor that caused major difficulties. This is described in the "Development Story" section below.

Believing that development of the electron microscope would require a budget of around 10 billion yen, Dr. Tonomura asked everyone involved to start working toward the formulation of a proposal for a major national project. With the aim of strengthening science and technology in Japan, the government set up a groundbreaking scheme for national projects in 2009 whereby 30 leading researchers would each be given budgets of several billion yen that they would be free to use as they wished over a five year period. This was called the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program) and began with a process for selecting the researchers. Dr. Tonomura set out to win selection under this scheme and was rewarded for his efforts with the prospect of being granted a budget of nine billion yen. Unfortunately, this coincided with a change of government, raising concerns that the project budget might be cut to about one-third of the anticipated sum. There was no chance of Dr. Tonomura building the instrument he envisaged for three billion yen. In the end, with cooperation from various different people and by cutting back his plans to include only the microscope development, and by excluding the application research planned for the completed instrument, the work was able to get underway with a budget of five billion yen.

At the same time, work continued on setting up the development program. A major problem was the question of where to base the development. All past electron microscopes had been first assembled in the factory for basic performance testing and then broken down to be reassembled at the customer site or at a Hitachi laboratory. However, given the limited development schedule and the fact that the microscope was not intended as a product to be sold to customers, consideration was given to the option of having all parts for the microscope purchased and assembled at Advanced Research Laboratory, Hitachi, Ltd. (as it was then known) in Hatoyama in Saitama Prefecture. An electron microscope consists of tens of thousands of parts, and the laboratory had no experience with assembling such a large piece of apparatus from its individual parts. To achieve this, dedicated staff were assigned to tasks such as purchasing and accounting and based at Hatoyama. Former staff involved in engineering work at the plant that Hitachi High-Technologies Corporation had at Naka at that time were also requested to relocate to Hatoyama. Because it was clearly impossible to do all the machining work at the laboratory, Mr. Matsui and experienced engineers from the prototyping department at Hatoyama consulted with precision engineering companies around Japan to request their assistance. Numerous engineers from companies such as Hitachi High-Technologies Corporation and Hitachi High-Tech Fielding Corporation, including people with experience from the development of the ultra-high-voltage electron microscope, were requested to relocate to Hatoyama via transfers or secondments to work on design, development, and assembly. Naturally, the project also included developers from Hitachi's Central Research Laboratory, Hitachi Research Laboratory, and Production Engineering Research Laboratory (as they were then known), with the team amounting to more than 30 people at its peak.

Project Beset by Series of Unanticipated Events

The project formally commenced in March 2010. They started by setting to work on the overall concept and on the design and fabrication of bulky components that would take a long time to manufacture. Simultaneously, preparations also commenced for the construction of the building that would house the electron microscope. Once these initial birth pangs had been overcome, the project appeared set to proceed smoothly. Unfortunately, they were beset by an unanticipated event. Isao Matsui, who was one of the originators behind the project and the engineer who had made Japan the home of the ultra-high-voltage electron microscope was found to have a scirrhous carcinoma of the stomach. He died in December 2010, less than two months after the diagnosis. This was a major setback for the development. The surviving engineers were overwhelmed by this development, and the most

Cable caught in flooding

Damaged factory

Fig. 6—High-voltage Cable Struck by Tsunami Just Short of Completion and State of Factory after Tsunami.
The high-voltage cable being manufactured at a factory located on the shoreline near Hitachi City port was rendered useless by the large tsunami. The ground floor of the factory building was inundated and was not able to return to operation immediately after the water receded.

shocked of all must have been Dr. Tonomura who had worked in tandem with Mr. Matsui to promote the project. Nevertheless, by spurring on the project team without betraying any outward signs of his distress, Dr. Tonomura and the remaining team members pressed on with the development despite the somber mood. The construction of a purpose-built building to house the electron microscope proceeded smoothly, and work started on the design and manufacturing arrangements for other bulky components, including the high-voltage cable, the "vessel on vibration isolators" on which the electron microscope was to be mounted to isolate it from external vibrations, and the high-voltage tank that would house the high-voltage components, under the auspices of the designers who had taken over from Mr. Matsui. On the other hand, the design and manufacturing arrangements for the many components of the electron microscope itself were progressing only slowly.

In March 2011, an engineer working on building the mechanical components raised the alarm, reporting that because most of the manufacturing drawings had yet to be supplied, if nothing was done, it would not be possible to arrange for the work to be done by the engineering subcontractors and still get it completed on time. Then, on March 11, just as a meeting was getting underway to overcome this problem, the team experienced a shaking unlike anything they had been through before. It was the Great East Japan Earthquake. The microscope building was in the middle of pouring concrete for the foundations when the earthquake struck. After confirming that nobody was injured and that there was no damage to existing buildings, the team rushed off to the construction site only to find that work had already resumed with no signs of anything untoward. Impressed by this dedicated professionalism, the team was instilled with a commitment to complete the electron microscope this building was intended to house, no matter what it took. While there was no notable damage in the Hatoyama region, component-producing factories in Miyagi and Ibaraki were in a bad state. The high-voltage cable that was close to completion thanks to use of technologies developed in the 2006–2008 project was inundated by the tsunami and no longer in a usable condition (see Fig. 6). Rebuilding the special 12.5-cm-diameter high-voltage cable, which topped the list of expensive components with long lead times, was tantamount to restarting the budget and schedule from the beginning. Miraculously, the backup cable had escaped the flooding, and in the end it was completed only about three months late thanks to the efforts of Hitachi Cable, Ltd. (as it was then known). Another narrow escape was had by the power supply manufacturer that was building components such as the ultra-stable high-voltage power supply and lens power supply, both seen as critical components of the microscope. The headquarters factory of this company was located close to Sendai Airport. However, although the scenes of the airport being inundated by the tsunami were repeated time and again on television over the following days, the images stopped just short of showing the factory site, and because communications were down, there was no way of confirming whether the company was all right. A few days later the news came through that the tsunami had fortuitously stopped just short of the factory and the completed power supplies were unharmed. Despite the shortage of gasoline and other daily necessities, they still managed to deliver the power supplies to

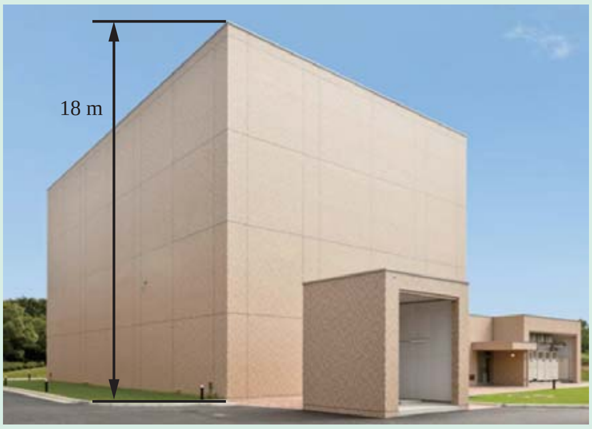

Fig. 7—Purpose-built Electron Microscope Building Providing Stable, Low-noise Environment.
The building provides sound insulation and low acoustic noise (20 dB or less above 200 Hz), reduced floor vibration (7.2 × 10^{-4} cm/s^2 at 100 Hz), and temperature variability in the vicinity of the microscope (ambient temperature) of ±0.2°C/8 h.

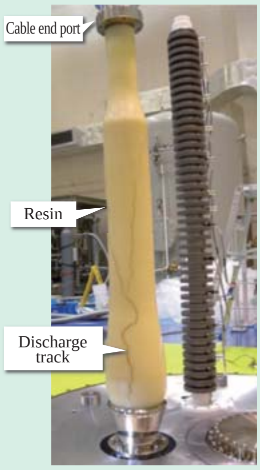

Fig. 8—Electrical Discharge Occurred at Tip of High-voltage Cable.
The end of the cable is at a high negative voltage while its base is grounded. When testing was performed by applying a high voltage to one end of the cable, a discharge occurred before reaching the rated voltage of 1.2 MV, causing a discharge track on the surface of the resin.

Hatoyama all but on time. The team members were so grateful they almost cried. When returning to Miyagi after the delivery, the team provided them with some supplies to take back for the people caught in the disaster. Although Hatoyama endured planned power outages that disrupted proper work for a time after the earthquake, the project team still came in to work nearly every day and continued getting on with what development they could. Nobody believed that anything worse could be yet to come.

It was a great shock then when it was revealed on March 16 that Dr. Tonomura had been diagnosed with pancreatic cancer. Bravely, Dr. Tonomura immediately passed on the news to the project team and pledged to return after his treatment. Trusting in these words, the team continued with the development. The delayed design of the electron microscope unit was able to proceed thanks to the efforts of everyone involved, rigorous progress management, and the reinforcements that made up for the lack of staff.

The following section tells the story of the development in chronological order, up to its completion.

Development Story —Overcoming Numerous Obstacles—

High-voltage Cable

The microscope building was completed on schedule in late August 2011 (see Fig. 7). The building succeeded in providing the required low-noise environment, with its floor vibration, acoustic noise, and temperature variation performance all coming in within specification. The temperature variation of ±0.2°C/8 h exceeded the target by an order of magnitude[23]. From then on, the major components were delivered one after another, to the point where the apparatus looked largely complete to an outside observer by the 2012 New Year. After the high-voltage cable that had been rebuilt following the tsunami damage was delivered and installed about three months late, live high-voltage testing at 1.2 MV was conducted on January 31 and February 7, 2012. Unfortunately, a major problem was encountered in the first stage of performance testing that made it impossible to apply the full voltage due to electrical discharges occurring at 900 kV and 600 kV (see Fig. 8). Because the cable had already passed 1.3-MV testing prior to delivery from the factory, these two discharges occurring at such low voltages were unexpected and very distressing. While there was a strong suspicion that the discharges were the result of foreign material, the apparatus had been assembled with great care and attempting any more rigorous measures for excluding foreign material would have been impractical. Even if some foreign material did still remain due to the current work environment and assembly practices, the voltage still needed to be applied. A joint team of high-voltage experts from within Hitachi and the cable manufacturer (Hitachi Cable) was quickly formed to work on the problem, and they embarked on a program of simulation and testing. An electric field simulation that was conducted to assess the influence of foreign material found that, unless metal fragments too large to miss (around 10 mm) were present, then the rated voltage should still have been possible. Another suspected cause was salt contamination in the insulators resulting from their being manufactured in a plant that had been restored after the tsunami damage. A sample component deliberately sprayed with saltwater was made and its insulation performance was tested only to find that no change whatsoever could be detected in the characteristics for the sort of salt levels found by the sea. As a result of ongoing investigations, and with advice from senior laboratory personnel, a dynamic simulation that considered changes over time found that the electric field at certain locations where it was expected to be close to zero was at times several tens of times higher. On a timeframe of several minutes to several hours after the voltage was turned on, the electric field at certain locations would increase temporarily. This phenomenon had been overlooked by the static simulations used for the design. Nevertheless the calculated electric field strength still did not reach the level that would trigger a discharge. Furthermore, this was in agreement with the fact that numerous live voltage tests had been conducted at the cable factory without discharges occurring. This led them to think that, while the increase in electric field strength was not on its own causing the discharges, they were likely being caused by a combination of other factors. It was concluded that small pieces of foreign material were one such factor, and the presence of residual air in component connectors was likely another. It is impossible to eliminate small pieces of foreign material and residual air entirely. However, because preventing the increase in the electric field at the problematic locations would be enough to prevent the discharges, it was decided to install electrodes for this purpose. By the time the modifications were completed and the voltage testing passed, it was already past July 2012. There were no further instances of discharges caused by the cable.

Death of Dr. Tonomura

After undergoing surgery in April 2011, Dr. Tonomura went into remission and was well enough to return to the laboratory six months later. A symposium to be attended by notable physicists and microscopy researchers from around the world was planned for May 2012 and everyone hoped that he would be able to attend as the event's host. Instead, he appeared before the project team for the final time in April 2012, passing away on May 2, 2012, just before the symposium was to start. This was at a time when the development team was focused on ways of dealing with the high-voltage cable discharge problem, and the news came through while it was at Hitachi Cable attending a meeting on the subject. Although rocked by this bad news, it was not unexpected because everyone involved in the development had, at Dr. Tonomura's insistence, been made aware of his condition, and so the work continued. The symposium, too, went ahead as planned, and included the playing of a video message recorded by Dr. Tonomura before his death. This loss of its principal investigator left the project with the problem of deciding who should take his place, putting the possibility of continuing the project in doubt. Accordingly, Nobuyuki Osakabe, who had racked up numerous notable results during his time working as a researcher in Dr. Tonomura's group and was at that time general manager of Central Research Laboratory at Hitachi, Ltd., appeared before the FIRST committee in the role of acting lead researcher to explain the situation and convinced them that the microscope would still be completed on schedule. As a result, the project was able to continue.

High-voltage Resistor Module

No sooner had the problem with the high-voltage cable been dealt with than a new problem emerged. This was the presence of noise indicating that small discharges were taking place, the problem being discovered by voltage stability measurements made after it became possible to operate with a voltage of 1.2 MV in late July 2012. To identify the cause of the noise, the large tank was opened and closed many times to enable a series of tests. An inspection of the components inside the tank found anomalous bulges on some of the nearly 100 resistor modules that were used to maintain stability at high voltage and to measure the voltage and provide feedback to the high-voltage control system. As noted in the section, "Four Major Obstacles to Overcome," development of these resistor modules to improve stability at high voltage had been completed prior to the commencement of the project. The module specifications stipulated high performance, including a temperature coefficient of resistance of ±2 ppm/°C and current noise of less than 0.3 ppm/min. The culprit was the silicone rubber molding material that had been selected on the assumption it would be suitable for these modules. Silicone rubber is porous, meaning it is easy for gas to pass through it. Because all of these components are held in SF_6 gas at high pressure (4 atmospheres), the gas permeates the silicone rubber, forming voids and cracks. The noise resulted because these voids cause small discharges (partial discharges) to occur. Although an attempt was made to fabricate alternative parts that could prevent void formation while still continuing to use the silicone rubber, this produced no signs of

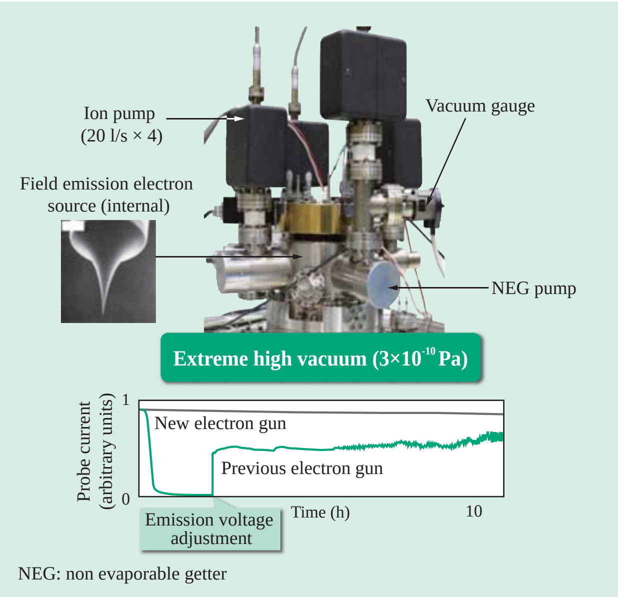

Fig. 9—Highly Stable High-brightness Electron Gun.
With previous electron guns, because the electron current drops off quickly after electron emission is initiated, it is necessary to adjust parameters such as the emission voltage and wait for stability to be achieved before it can be used. In contrast, by maintaining extreme high vacuum, the new electron gun achieves stability and is ready for use immediately after initiating emission of the electron beam.

improvement. When an investigation was conducted in parallel with this to track down information about resin molds, which included web searches rather than restricting itself only to in-house sources, it returned a search result for a doctoral thesis from The University of Tokyo. In a case of the answer being close at hand all along, the author is a researcher at Mechanical Engineering Research Laboratory, Hitachi, Ltd. (as it was then known). Based on the researcher's advice, the team gave up on silicone rubber and went back to using tried and tested epoxy resin. However, resistors embedded in epoxy resin are subject to stresses as it hardens, with the risk that this will degrade their temperature coefficient of resistance. Nevertheless, the target performance was achieved by making changes to the coating material and shape of the resistors to minimize these stresses. It took until August 2013 before the team was confident that this would resolve the problem and eliminate the noise that was causing difficulties for high-voltage stability testing. However, problems continued, with a major discharge occurring when operating at 1.2 MV after the new resistors were installed. The source of the discharge was the newly manufactured resistor modules, caused by the presence of abnormal protrusions or metal fragments due to soldering defects in the modules. There was also a problem with the testing method used to determine how high a voltage each module could withstand. A full set of modules believed to be compliant finally became available only after improvements were made to the manufacturing process in discussion with the supplier, and changes to the orientation of the electric field were applied during testing.

Highly Stable High-brightness Electron Gun

Fortunately, the development of the highly stable high-brightness electron gun described in the section, "Four Major Obstacles to Overcome," proceeded without any dramatic incidents, achieving the target of an extreme high vacuum of 3×10^{-10} Pa in January 2013, roughly on schedule. Testing confirmed that a stable electron beam could be generated for 15 or more hours at a time without needing recalibration[(24), (25)] (see Fig. 9).

Contamination of Acceleration Tube

In the spring of 2013, at the same time as the team was going back to using epoxy as the mold material for rebuilding the resistor modules, progress was being made on getting the acceleration tube working. The acceleration tube is a 1.8-m-high cylindrical component made up of 44 layers of electrodes and insulators. There is a high potential difference across each layer (approximately 30 kV), with the topmost electrode having a potential of –1.2 MV and the bottommost electrode a potential of 0 V. The electron beam is accelerated as it travels from the top to the bottom of the tube, the interior of which is maintained at ultra high vacuum in the 10^{-9}-Pa range. Although it has been estimated that the acceleration tube could withstand potential differences across each layer as high as around 80 kV under ideal conditions, at the time they were delivered from the supplier, stability could only be maintained up to 20 kV due to factors such as residual gases, protrusions, or fragments of foreign material in the insulators and in the joints between the electrodes and insulators. Accordingly, the acceleration tube (with its interior kept in a state of ultra high vacuum) was first placed inside a large chamber equipped with a heater and baked to drive out any gases, then voltages were applied across each layer to deliberately induce a small discharge and thereby expel any foreign material and smooth out any protrusions. This improved the performance of the acceleration tube to the level needed in practice, which was to be able to operate stably for long periods of time with voltages of 30 kV or more across each layer. An inspection of the acceleration tube after the final baking in May 2013 found discoloration (browning) on the exterior of the insulators. While the reduced ability to withstand high voltages was not fatal, some layers had degraded somewhat or were subject to an increasing number of micro discharges, causing noise. An analysis of the discolored material found it to contain metallic copper and copper chloride. Eliminating this copper entirely would have required shaving off a layer of skin from the surface of the acceleration tube insulators, washing them again, and repeating the baking process, a job that would have taken months to complete for such a large component. With only 10 months of the original development schedule remaining, this would have removed any hope of achieving the original objective of world-leading resolution by March 2014. Although there was a chance that performing repeated baking cycles without first removing the contamination would be enough to achieve the desired voltage, when the implications of failure were considered, it was decided instead to go back to fundamentals and look at causes and countermeasures. The problem-solving work, too, was aided by knowledge from Hitachi laboratories and the capabilities of the analysis team. The jobs of analyzing and identifying materials, identifying which material was causing the problem, and determining the mechanism of copper adhesion and how to stop it were completed in less than two months. The reprocessing and cleaning of the acceleration tube were completed around the same time, so thanks to the reapplication of a voltage to the tube and the success of baking at the increased voltage it could withstand, it had become possible to operate stably at a voltage of 1.2 MV by the end of December 2014. Two years had elapsed since the live testing of the high-voltage cable. The FIRST project ran up to March 2014, and it was looking like achieving the target resolution by that date would be impossible no matter what they tried. However, by making the case that, although the date for achieving the target resolution had been put back to the 2014 fiscal year, it would definitely be achieved, they succeeded in convincing those involved. They set out to produce 1.2-MV electron microscope images before the end of the fiscal year, and achieved this goal on March 12.

Taking on Challenge of Achieving World-leading Resolution

Operation of Aberration Corrector

Once the basic set of functions for the electron microscope had been demonstrated, the next challenge was to achieve world-leading resolution. If all worked to its design specifications, the resolution should be in the 40-pm range. Although factors such as the stability at high voltage, installation conditions, electron beam stability, and the operation of the aberration corrector had been checked individually, it was not until system testing was performed that they would find out how well these would function when working all together. The aberration corrector is one of the key components of the microscope but its performance cannot be determined until the electron microscope itself is operating at close to its target performance. To achieve this, the aberration corrector was removed temporarily and the performance determined for the electron microscope on its own. It took until July 2014 before the aberration corrector was put back and its performance tested.

Achievement of World-leading Resolution

Although resolution of 60 pm had already been achieved by August, subsequent progress was slow, improving to no better than 50 pm by October. Around this time it was announced at the International Microscopy Congress held in Prague in September that a team from The University of Tokyo and another company had reduced the world record for electron microscope resolution from 47 pm to 45 pm[26]. This increased the pressure on the team to achieve world-leading resolution. Another piece of news was that a FIRST ex-post assessment hearing was scheduled for November 26. It was vital that world-leading resolution be achieved before this date. The inability to improve resolution beyond 50 pm was believed to be due to a combination of factors: the static performance of the stage, external electrical noise, and damage to the specimen caused by the electron beam. In other words, it was believed that while the microscope had the necessary potential for performance, this had not yet been realized. Accordingly, the team adopted a strategy of imaging a large number of locations in as short an exposure time as possible. The specimens being used consisted of gallium nitride (GaN) crystals that had been formed into a wedge shape by partitioning in order to image the atoms at its peak (a thickness of several nanometers). However, exposing the specimen to the electron beam for too long caused its structure to be disrupted by the beam's energy. Accordingly, they adopted a practice of first focusing the electron beam at a separate location and then quickly redirecting it to the location to be observed in order to image a large number of sites, each several atoms thick, in the style of random sampling. This

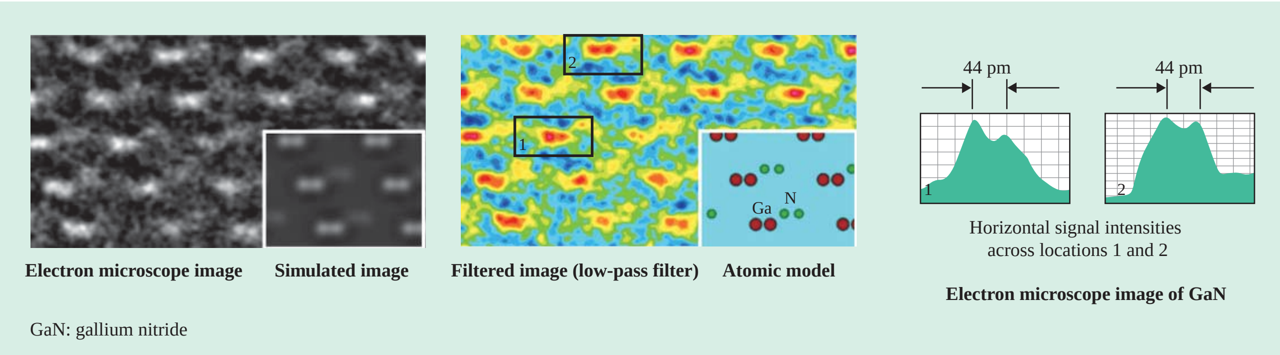

Fig. 10—Imaging of Ga Atom Spacing in GaN.
To determine the actual resolution of the electron microscope, it was used on monocrystalline GaN to capture an image of the 44-pm spacing between Ga atoms.

Fig. 11—Atomic-resolution Holography Electron Microscope.
The photographs show the three large high-voltage tanks (top-left), the electron microscope operation console (bottom-left), the electron microscope itself (lens, specimen stage, detector, etc.) (center), and the electron microscope viewed from the front (right).

succeeded in imaging the 44-pm spacing between Ga atoms (see Fig. 10). By this time it was already November 14, but it was in time to report a world-leading resolution of 44 pm at the ex-post assessment hearing. Next, the team started preparing to submit a paper to a scientific journal in order to announce their results publically as soon as possible. However, when considering the resolution of a transmission electron microscope in an academic context, rather than just being able to see the gaps between atoms, what is required are images that clearly indicate the lattice spacing of the crystal. A subsequent experiment performed using monocrystalline tungsten improved on the 44-pm record by imaging a lattice spacing of 43 pm with good repeatability. A paper including this data was submitted to a journal, *Applied Physics Letters*, in early January 2015, and received an unusually prompt response confirming its acceptance by the end of the month[27]. With the news also appearing in newspapers on February 18, the date of publication of the paper, the instrument was finally recognized as the electron microscope with the world's highest resolution. Fig. 11 shows the main components for the completed atomic-resolution holography electron microscope.

NEW REALMS OPENED UP BY ATOMIC-RESOLUTION HOLOGRAPHY ELECTRON MICROSCOPE

While this article has focused on resolution, which is the simplest expression of microscope performance, in fact the real value of the instrument comes not merely from its world-leading resolution, but also from its ability to make quantitative measurements of electromagnetic fields at atomic resolution. Materials are made up of atoms, and their properties are determined by the types of these atoms and how they are arranged, and by the fields they produce. The key to the successful development of advanced functional materials that provide new functions or outstanding performance lies in determining how atoms are arranged and the associated fields. Because it is particularly common for the electromagnetic fields inside materials be a major determinant of their characteristics, it is important to measure electromagnetic fields at the atomic level. Examples include the electrode materials used in rechargeable batteries, magnets and superconductors, and thermoelectric conversion materials (see Fig. 12). Developments such as improvements to the performance of these materials or the commercialization of new materials will transform society by dramatically improving the performance of the many systems that use them.

One example is the high-performance magnets that play an important role in making hybrid-electric vehicles and electric vehicles viable. There is a need to find new magnets that can outperform the

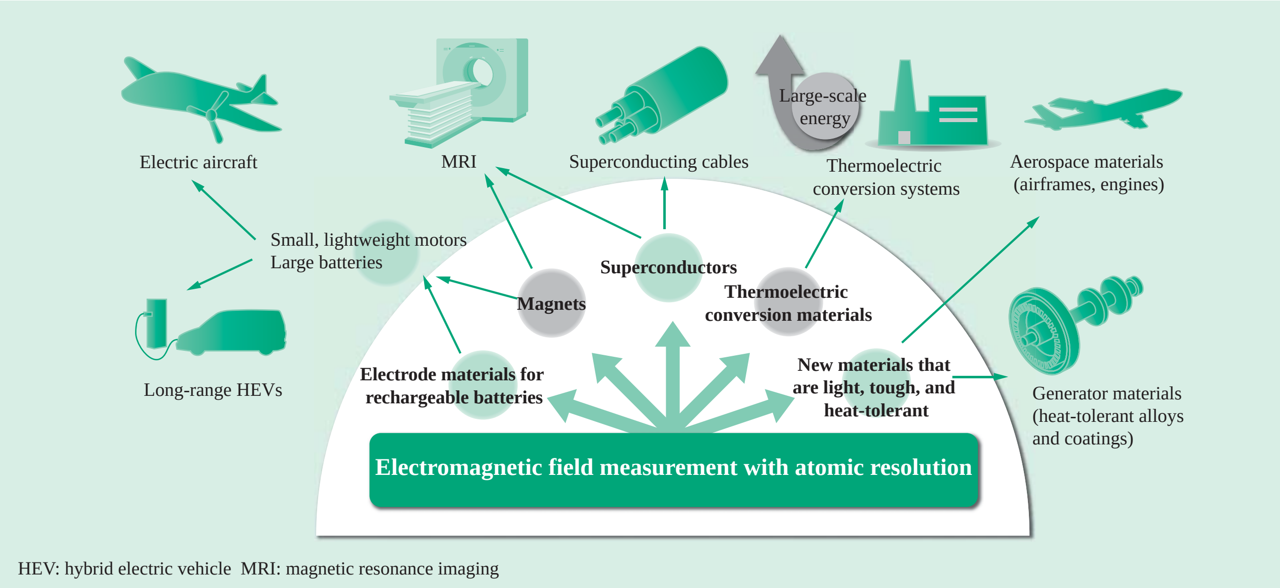

Fig. 12—Possibilities Opened up by Electromagnetic Field Measurement with Atomic Resolution.
The performance of new functional materials that underpin energy-saving and resource-saving innovations, such as magnets, superconductors, and thermoelectric conversion materials, is closely related to the behavior of electromagnetic fields in microscopic regions inside these materials. Through the elucidation of these mechanisms, electromagnetic field measurement with atomic resolution will lead to the development of groundbreaking new materials.

neodymium magnets used currently. Along with improving performance at room temperature, there is a need for materials that can be used in harsh conditions with high temperatures or strong magnetic fields. To develop magnet materials like these, it is important to determine the arrangement of the atoms from which they are made and the resulting magnetic properties so as to gain insights into which materials to use, their composition, and manufacturing techniques. Viewing magnetic fields at the atomic level has become essential to achieving this. As described above, the atomic-resolution holography electron microscope will drive the development of new materials, not only for resolving problems such as energy and the environment, but also for making life more comfortable and convenient. It is also anticipated that the development of these advanced and groundbreaking materials will facilitate progress in fundamental science. Hitachi intends to undertake research into these applications through open innovation in conjunction with leading research institutions in Japan and elsewhere. For example, Hitachi intends to work on groundbreaking material developments and the elucidation of their physics by working with research institutions in Japan and elsewhere, such as RIKEN, with which Hitachi is already working on research into techniques for using the holography electron microscope.

CONCLUSIONS

The atomic-resolution holography electron microscope is now complete. Tragically, both Dr. Tonomura, who came up with the concept for the microscope, and Isao Matsui, who, as an engineer, turned the concept into reality, were felled by illness before the microscope was finished. As described in this article, the project also faced numerous technical difficulties that brought its very completion into doubt any number of times. The depth of Hitachi's research and development and "monozukuri" manufacturing know-how; the extent of its practical capabilities; and its tradition of unstinting collaboration were all demonstrated by the fact that these difficulties could be overcome to complete the microscope. It is also thanks to the support of academics at numerous universities and other research institutions, the staff of supporting institutions, and the willingness of the staff of companies from outside the Hitachi Group to work alongside Hitachi to confront difficult manufacturing challenges. The author would like to express his heartfelt gratitude for this assistance.

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