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ADVANCE

Human-artifacts Symbiosis in Society 5.0

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Changes for the Better

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Human-artifacts Symbiosis in Society 5.0

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CONTENTS

Technical Reports

Precis

The trend toward automation and labor saving is accelerating due to the Covid-19 pandemic, in addition to the labor shortage caused by the declining birthrate and aging population. Equipment is being automated in various ways and can now handle more complicated operations.

To achieve sophisticated automation, large amounts of sensor data are necessary, while AI and IoT need to be fully utilized to manipulate equipment appropriately.

This special issue introduces technological developments that are paving the way toward a super-smart society as well as new relationships between humans and modern equipment.

Smart Technologies for Coexistence between Humans and Robots in Buildings

Authors: *Yuji Igarashi*, Hiroshi Taguchi*, Tomoaki Takewa*, Mitsuhiro Yamazumi** and *Noritaka Okuda**

1. Introduction

In Japan, to cope with the decreasing working-age population due to the declining birthrate and aging population, robots that work autonomously instead of humans are being considered. Mitsubishi Electric Corporation has been developing technologies for using robots in buildings. If multiple robots move in a building, they may pass each other in a narrow passage or get on and off an elevator. If the robots are large, they may become deadlocked and come to a standstill. Furthermore, if robots use elevators during commuting hours or other busy periods, they may hinder human movement. This paper describes a robot and building facility cooperative control technology[(1)(2)] being developed by Mitsubishi Electric to solve such problems.

2. Robot and Building Facility Cooperative Control Technology

2.1 Outline

The robot and building facility cooperative control technology allows robots to travel safely in buildings and thus work more efficiently by using information on the positions of humans and robots in the buildings, operation data of elevators and other equipment, and building maps. Figure 1 shows the structure of the robotic control and guidance system in a building using this technology. The system consists of the following functions: (1) a function for managing dynamic map data in a building, which manages the positions of humans and robots and the operation statuses of elevators and other equipment in real time, (2) a route searching function that calculates the paths that the robots can travel along in the building, (3) a behavior planning function that creates behavior plans for robots to maximize their operation efficiency in the building, (4) a guidance and control function that informs the robots of travel paths and gives them travel instructions, and (5) an infrastructure-linked travel control function by which the robots select an appropriate speed and path based on the indoor travel environment using information (map data of the travel paths) provided by the control and guidance system.

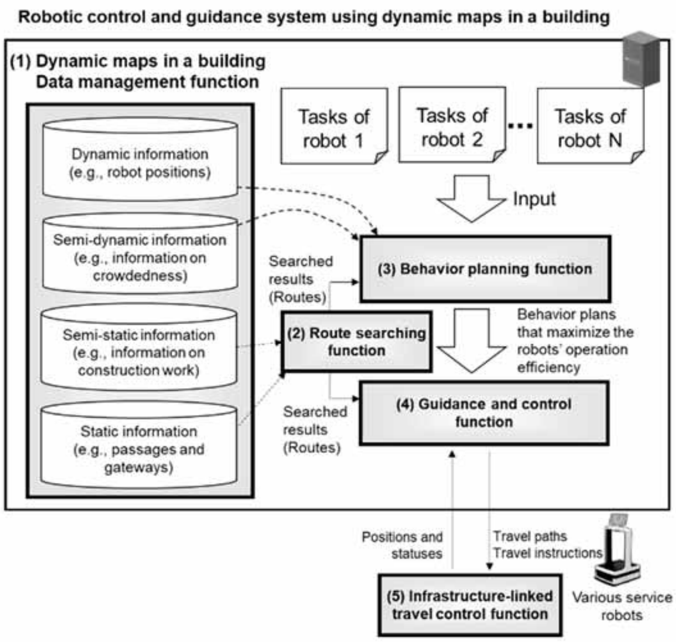

Fig. 1 Robotic control and guidance system

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2.2 Robotic control and guidance system using maps in a building

This section describes the five functions of the robotic control and guidance system described in Section 2.1.

2.2.1 Function for managing dynamic map data in a building

Dynamic map data in a building is indoor map data developed independently by Mitsubishi Electric. In the data management method, the map data is classified into four levels based on the data update cycle: static, semi-static, semi-dynamic, and dynamic information (Fig. 1). Static information includes information on fixed objects (e.g., wall surfaces, floor surfaces, elevators, and gateways) in the building; semi-static information includes information in units of days and hours (e.g., information on construction work and elevator maintenance); semi-dynamic information includes information in units of hours and minutes (e.g., information on crowdedness and cleaning); and dynamic information includes information in units of minutes and seconds (e.g., information on the positions of robots and humans and elevator operation). In addition, the contents and format of dynamic map data in a building conform to the "Data specifications of indoor geospatial information expressed for each floor (draft)" issued by the Geospatial Information Authority of Japan, which the Japanese Ministry of Land, Infrastructure, Transport and Tourism is using in a project for turning digital indoor maps into an open database.[3] Therefore, digital indoor map data on public facilities can also be used.

2.2.2 Route searching function for robots in a building

This function uses network data (links and nodes) included in static information of the dynamic map data in a building as shown in Fig. 2 to search for a route to the node closest to the specified destination. Passable direction(s) and distances are set to each link and Dijkstra's algorithm is used to search for a route with the shortest travel distance to the destination. If some links cannot be used due to construction work and elevator maintenance for which information is included in the semi-static information of the dynamic map data in the building, then the links are excluded from the search targets. This enables passable routes to be calculated for each situation. The searched results are used by the behavior planning function (Section 2.2.3) and by the guidance and control function (Section 2.2.4).

2.2.3 Function for planning behaviors of robots in a building

To provide a comfortable travel space for both robots and humans in a building, it is necessary to maximize the total operation efficiency of the robots without hindering the movement of humans. To realize this, when planning the behavior of each robot, time periods during which elevators get crowded are estimated based on statistical information on elevator use and constraints are determined. Examples of such constraints include "the robots must not use elevators at crowded times" or "the maximum number of elevators used by robots during crowded times shall be limited." For example, as shown in Fig. 3, during a time period when elevators get crowded, the robots only perform charging or tasks. By planning robot behavior and giving them instructions in this way, it is possible to keep the travel environment comfortable for both humans and robots while maximizing the number of tasks that the robots perform.

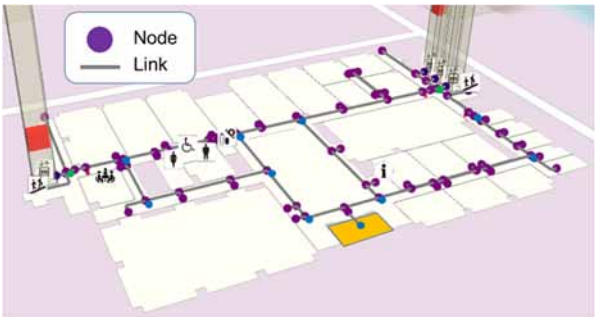

Fig. 2 Example network data of dynamic map in a building

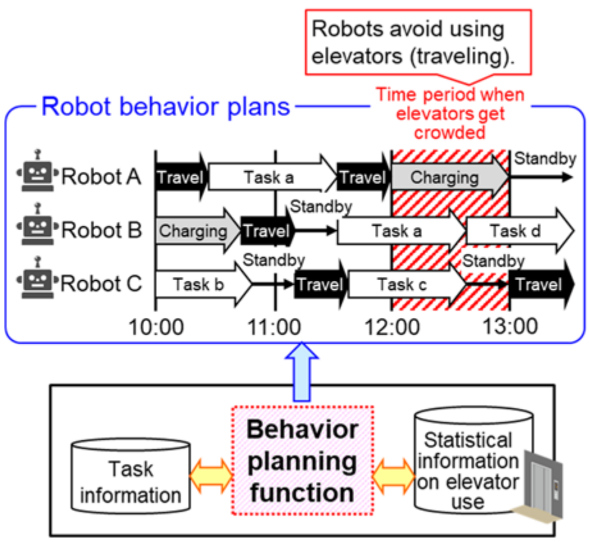

Fig. 3 Planning function of robot behavior

2.2.4 Function for robot guidance and navigation in a building

A building may have narrow passages or areas where multiple robots cannot pass at the same time (collision path in Fig. 4). Even if a constraint is determined, for example, by limiting the number of robots that can travel on the collision path at the same time to one using the behavior planning function, the travel times of robots may be disrupted by having to wait for elevators. Therefore, there is no guarantee that the robot can travel on the collision path at the scheduled times. Consequently, this guidance and control function obtains information on the robot positions at intervals of approximately one second: when two or more robots are expected to enter a collision path at the same time, the function stops one of the robots before it enters the path and gives the other priority to use the path, realizing smooth indoor robot travel.

2.2.5 Function for a corporative navigation between mobile robots and building platforms

Our guidance system publishes not only coordinates of points (nodes) but also width, direction and traffic rules and then robots can control adaptively in building platforms by restricting a navigation route search area by situations and improving localization accuracies by geometries. As a result, robots enable to pass through elevators' narrow doors safely (Fig.5).

2.3 Technologies for the safety and security of robot travel

This section describes technologies that support the safety and security of the robotic control and guidance system.

2.3.1 Indoor positioning using surveillance cameras

When multiple robots co-exist, it is necessary to prevent them from colliding with one another in a passage or elevator. To ensure this, Mitsubishi Electric has developed an indoor positioning technology in which surveillance cameras in the building are used to recognize the tags attached on robots, and the distance from the cameras to the tags and orientations are calculated with high accuracy in real time. This technology can identify a robot by reading its ID tag, and can also measure its position. An experiment using Mitsubishi Electric's MELOOK3 NC-7620 surveillance camera has confirmed that this indoor positioning technology can detect the positions of robots in an indoor area measuring 3.0 m long by 5.0 m wide by 2.7 m high accurately and quickly. The average position error is 15 cm or less and the positioning time is less than 100 ms (Fig. 6).

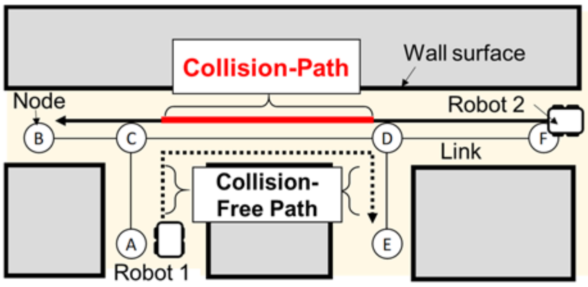

Fig. 4 Area where robots cannot pass at the same time

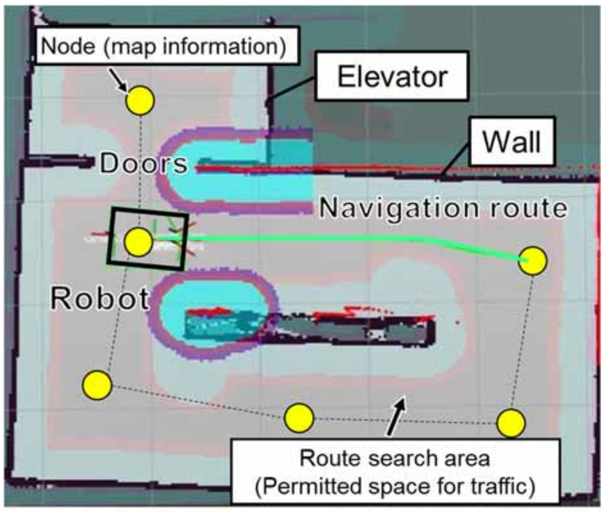

Fig. 5 Searching for a robot's navigation route using map information

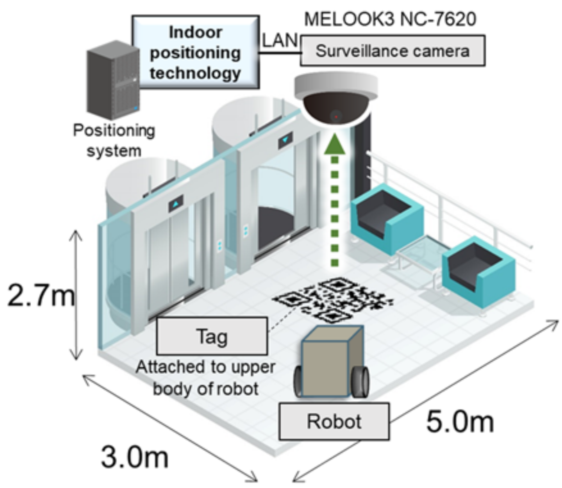

Fig. 6 Indoor positioning technology for robots using surveillance cameras

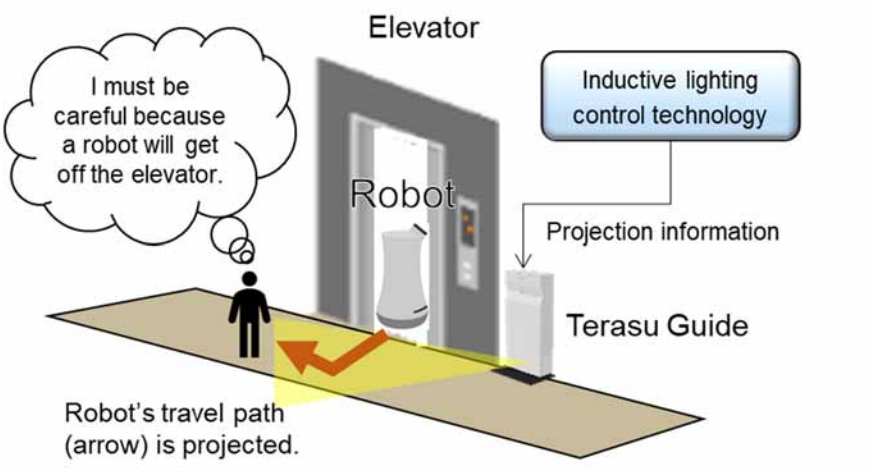

Fig. 7 Example of using inductive lighting control technology

2.3.2 Inductive lighting control for safe travel

Humans and robots must be able to travel safely when coexisting in a space. For example, when a robot gets off an elevator, it must not collide with someone entering the elevator. Mitsubishi Electric has been developing "Terasu Guide", a projector-based animation lightning system, and will develop an inductive lighting control technology using Terasu Guide to avoid collision and ensure safe travel by humans and robots. In the inductive lighting control technology, an image of a robot getting off an elevator is projected onto the floor or wall in front of an elevator (Fig. 7). The technology uses robot position information and scheduled travel paths to determine in advance which floor the robot will get off and at what time, and projects the image at the appropriate time. This will give users of facilities in a building intuitive and easy-to-understand information to help them travel safely and easily.

3. Conclusion

This paper described a robot and building facility cooperative control technology being developed, focusing on the control and guidance system for robots in a building and elemental technologies for safe operation of the system. Currently, Mitsubishi Electric is conducting a demonstration experiment using these technologies (Fig. 8). We will keep improving the technologies and create new solutions to realize a sustainable society that offers safety, security, labor-saving, automation, and higher productivity.

Fig. 8 Proof of concept

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Development of Remote Machine System with Sense of Oneness

Authors: *Masaki Haruna*, Koichi Hata*, Noboru Kawaguchi**,*
*Masaki Ogino**** and *Toshiaki Koike*****

1. Introduction

Developed countries including Japan are facing labor shortages due to the decreasing population, declining birthrate, and aging. One solution is autonomous robots, and there are expectations for the application of artificial intelligence technologies to robots. Regarding mobile technologies in particular, the progress of Google's autonomous driving as well as legged movement by Boston Dynamics and MIT are remarkable. The authors have confirmed in a study that artificial intelligence technologies can be used to acquire autonomous driving behavior from human driving behavior.(1)

However, it is estimated that achieving precise autonomous manipulation that can replace human hands will take several decades. There is increasing social need for technologies that can operate remote machines to ensure safety and security for people. Such technologies could help solve labor shortages; maintain and inspect remote observation stations for frequent natural disasters; and perform physically and mentally stressful tasks such as removing unexploded ordnance and improvised explosive devices and performing disinfection for COVID-19. In recent years, remote operation has been gaining attention due to the advancement of virtual/augmented reality (VR/AR) and communication technologies. Research started in the 1940s on operations in environments exposed to radiation, and in the 1980s, teleexistence and telepresence emerged thanks to the advancement of electric and computer technologies. Surgery-assisting robots have recently entered practical use. However, there is no system for remotely operating machines that can be used in place of human operations.

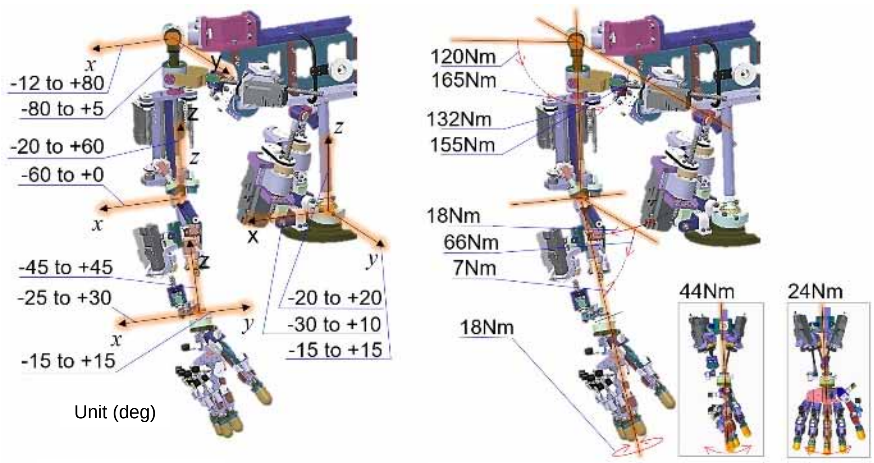
2. High-Power Humanoid Remote Control Robots

We have created a prototype humanoid remote control robot with 42 degrees of freedom (DOFs). Our self-locking mechanism, which was developed for high-accuracy driving of heavy objects in the large telescope business(2)(3), is used for the hands and our linear link mechanism is used for the upper body. Each joint of the 11-DOF mechanical hand has a high-reduction worm gear and the hand can grasp an object stably and according to its shape. Each joint of the 17-DOF mechanical upper body (except the hands) has a linear link mechanism, which can produce a high thrust force even with a limited volume and mass. Figure 1 shows the drive range and thrust design values.(4)

3. Simple Operation Interfaces (I/Fs) for Intuitive and Delicate Operations

3.1 Intuitive motion transmission I/Fs

To perform operations involving the hands, it is important to transmit the positions of the fingers of an operator and the operator's orientation to the robot hands accurately as motion transmission. There are two



Drive range (deg) **Driving torque (Nm)**

Fig. 1 Prototyped humanoid remote control robot

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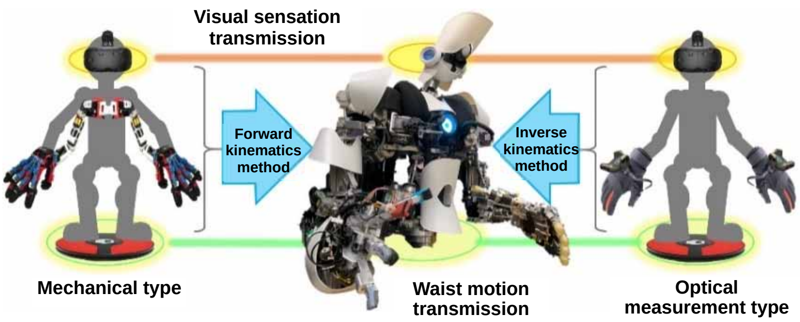
methods of achieving motion transmission: forward kinematics and inverse kinematics. We prototyped a mechanical type operation I/F that uses small arms as the forward kinematics method and an optical measurement type operation I/F that can measure 6 DOFs in the space at the fingers of an operator as the inverse kinematics method to verify motion transmission (Fig. 2(a)). The mechanical type operation I/F enables all joint angles to be created intuitively when an operator moves the small arms with the same structure as the robot. Its advantages include no need for mathematical operations and high measurement stability. A disadvantage is that the weight of the operation I/F itself places a load on the operator. Meanwhile, advantages of the optical measurement type operation I/F are that only space measurement of the fingers is required, and the simple I/F applies less load on the operator. Meanwhile, countermeasures for redundant DOFs, joint driving limit, and other factors are required. Optimum operation I/Fs can be provided by selecting a motion transmission I/F and combining and switching them based on the application.

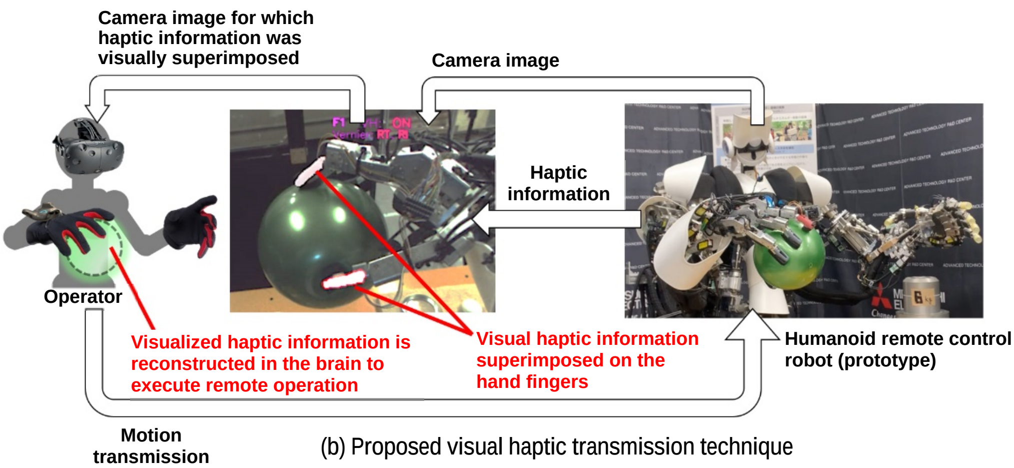
3.2 Simple visual haptic transmission technique that enables delicate operations

3.2.1 Existing haptic transmission technologies

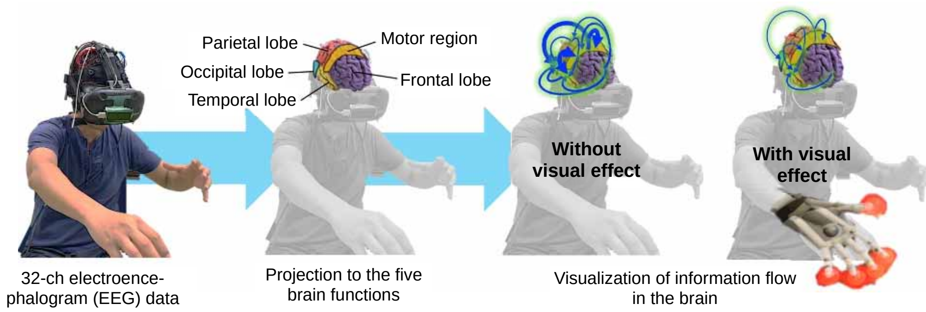
Methods of physically transmitting haptic information of remote machines include the installation and glove types. HaptX Gloves in particular are outstanding: the cutting-edge commercially available glove developed by HaptX Inc. has 30 points of force feedback (F/B) at each finger. However, the system



(a) Two motion transmission I/Fs for finger positions and orientation of operator



(b) Proposed visual haptic transmission technique



(c) Process of analyzing electroencephalogram data on operability

Fig. 2 Developed technologies for motion and sensory transmission and evaluation includes a compressor and so tends to be large. In addition, regarding human haptics, it has been shown that deep sensation is also important in addition to the cutaneous sensation stimuli on the outermost layer.

3.2.2 Proposal of a visual haptics technique

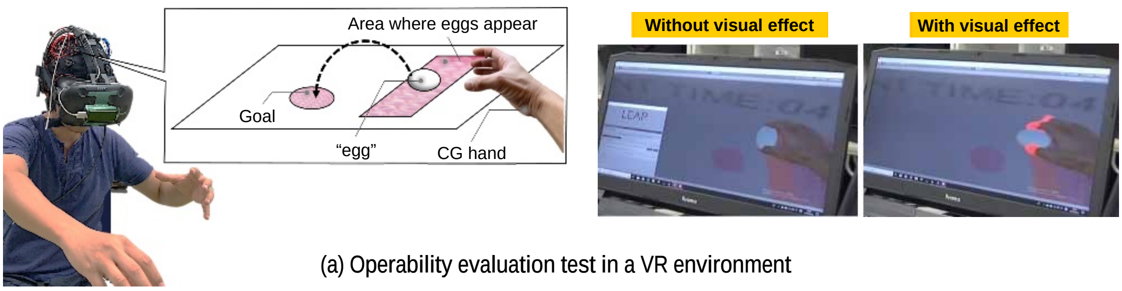
It is known that human haptic cognition is closely related with visual sensation. The da Vinci surgical system has shown that surgical operations are possible even without physical haptic information. Based on this knowledge and the authors' experience, in this project we aimed to simplify the operation interfaces and make them easier to use by superimposing haptic images on robot camera images using AR technologies as shown in Fig. 2(b).(5) To our knowledge, this approach of superimposing visual haptic information on the contact points of the robot fingertips is unique. In addition, this technique involving AR can visually notify operators of the contact status of the robot fingers even for operations involving a shield.

3.2.3 Operability evaluation by electroencephalogram measurement

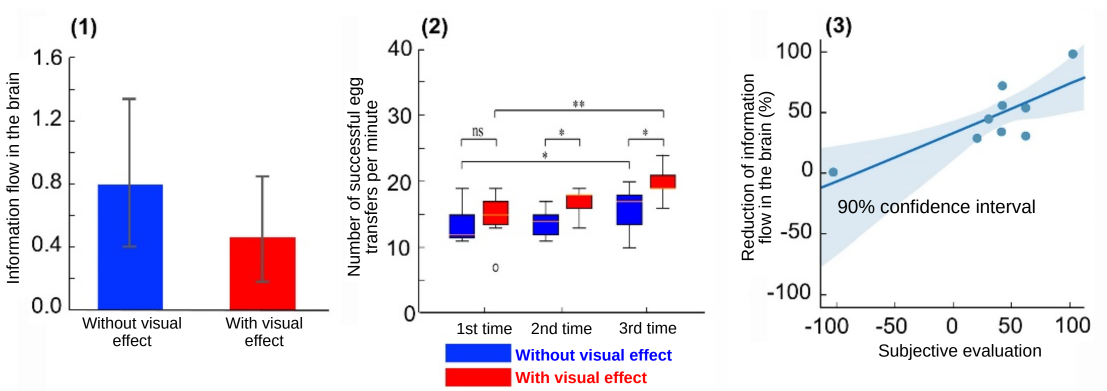
The operability of the proposed technique in which visual haptic information is superimposed on the contact points of the hands was analyzed and evaluated using electroencephalogram (EEG) measurement data and the smooth coherence transform (SCoT) library. SCoT is a technique for establishing a stationary vector autoregressive model from electroencephalogram data obtained by an electroencephalogram sensor and estimating the correlation of connectivity of brain signals. In this analysis, 32-channel electrodes were spatially mapped to cover most of the scalp as specified by the international 10-20 system to measure data. Then, projection to the five locations of the frontal, occipital, parietal, temporal, and motor regions was performed. To analyze the relationship of the connectivity of brain signals, the full frequency directed transfer function (ffDTF) was used. The directions of flow of the brain signals in these five regions (time order of excitation) are indicated by arrows and the amount of information flow is expressed by the thickness of the arrows. In this paper, the flow direction and amount of brain signals are called "information flow in the brain (without unit)" (Fig. 2(c)).

The operability with and without visual effect was evaluated in the VR environment shown in Fig. 3(a). In this game, a subject moved eggs that successively appeared to the goal area for one minute. The results showed that the visual effect reduces the information flow in the brain by 45% and accelerates "getting used to" (Fig. 3(b-1) and Fig. 3(b-2)). In addition, the subjective evaluation by the subjects was highly correlated with the reduction of information flow in the brain (Pearson correlation factor: 0.795, p-value: $0.011 < 0.05$). Thus, the results confirmed that electroencephalograms can be used as a quantitative index for evaluating operability(5) (Fig. 3(b-3)).

Furthermore, the operability was evaluated for three modalities: sound (loudspeaker) for which human response was considered to be high; vibration (motor), which is one type of physical haptic F/B; and light (LED)



(a) Operability evaluation test in a VR environment



(b) Evaluation results

Fig. 3 Evaluation results with and without the proposed visual haptics technology as visual F/B of the proposed technique (Fig. 4(a)). The results show that the grasping force is the smallest for the LED and so the operability with the LED is high (Fig. 4(b-1)). In addition, as a subjective evaluation, many subjects said that the concentration of information into the remote operation space improved the operability and the LED was most highly valued (Fig. 4(b-2)). Regarding information flow in the brain, the vibration and LED were at the same level (Fig. 4(b-3)).

These evaluation results have confirmed that the proposed technique to superimpose visual haptic information on the contact points of hands as sensible F/B can reduce the cognition load for operators while minimizing the operation I/Fs, and it works well for intuitive and delicate operations.[6]

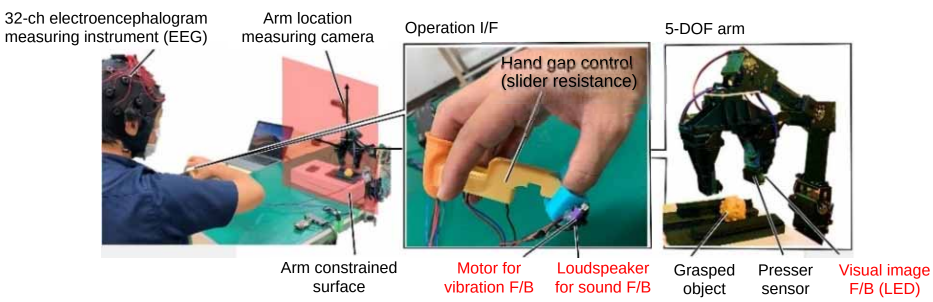
4. Verification of Operations with the Prototyped Humanoid Remote Control Robot System

The hands with self-locking mechanisms could grasp a ball, aluminum container, stone, and other objects stably (Fig. 5(a)). In addition, the use of the linear link mechanism in each joint shaft except the hands enabled high output in a limited volume. The robot could grasp and transfer a 6-kg or heavier object with one arm (Fig. 5(b)). Furthermore, human control via the intuitive motion transmission I/F allowed the robot to perform even a new task flexibly (Fig. 5(c)).

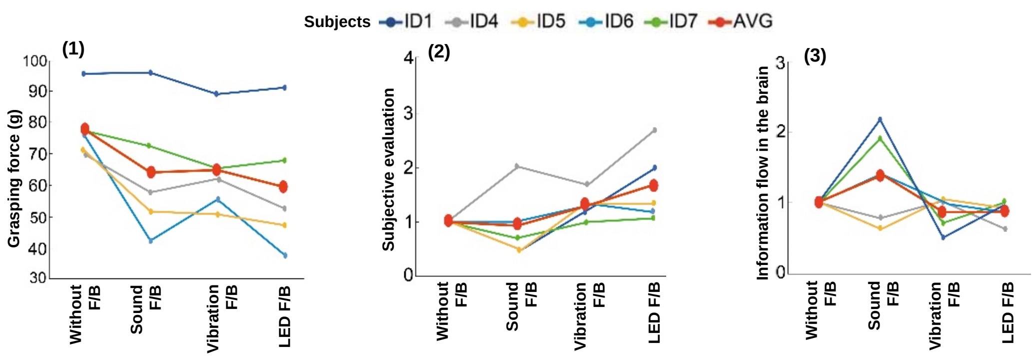
The proposed visual haptics technique was verified for three types of delicate operations: transferring a raw egg, potato chip, and card, and for grasping an alcohol container (Fig. 5(d)). The visual haptic information changes based on the grasping force. It has been confirmed that for all the objects, by seeing such changes in the colors of the hand fingers it is possible to grasp and transfer an object with appropriate force and the contact status of the robot fingers can be visually shown even for operations involving a shield.

5. Conclusion

This paper proposed a high-power humanoid remote control robot featuring technologies that we had developed for the large telescope business, motion transmission I/Fs for operating the robot intuitively, and a simple visual haptic transmission technique that enabled delicate operations. It also presented the results of an effectiveness demonstration by electro-encephalogram measurement. It was demonstrated that the system with these elemental technologies can grasp and transfer a 6-kg or heavier object and a potato chip, for which the grasping force for transfer needs to be finely adjusted. Based on the progress of virtual/augmented reality (VR/AR) and global communication technologies, we aim to introduce remote machine operation systems into society that provide people with safety and security for physically and mentally stressful tasks, and that can help achieve a work-life balance that contributes to human happiness. These features were learned through the Small World Project,[7] which was based on the developed technique. Remote operation technologies can digitalize a person's intentions and motions, and

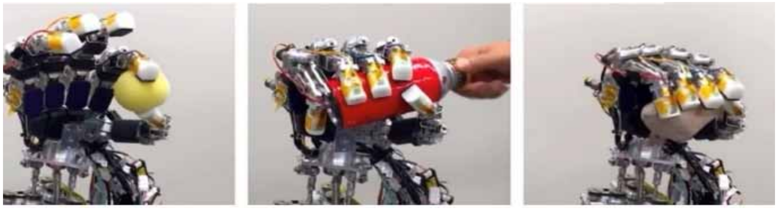


(a) Evaluation devices

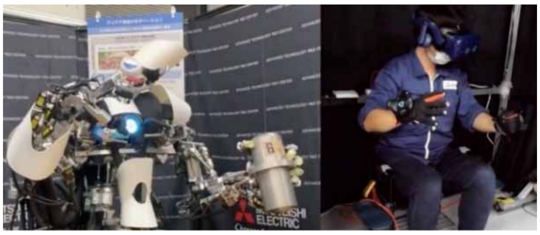


(b) Evaluation results

Fig. 4 Comparative evaluation test of modal F/B for "sound", "vibration" and "light" for haptics sensation



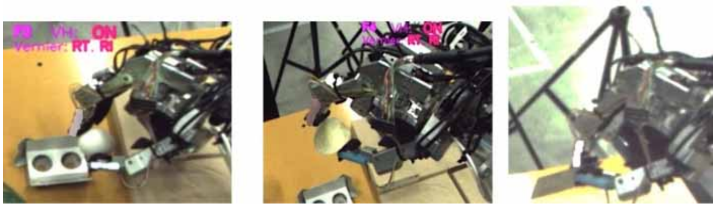
(a) Stable grasping by a hand with the self-locking mechanisms



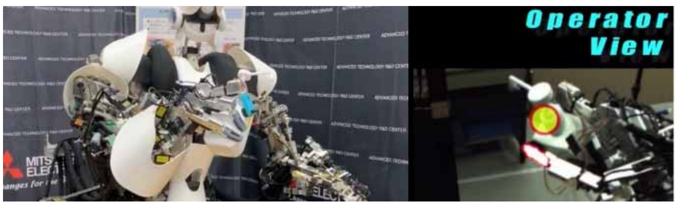
(b) High-power humanoid remote control robot that can grasp and transfer a 6-kg or heavier object with one arm

Toggle switch manipulation　Fastener manipulation　Cylinder insertion

(c) Flexibly perform various tasks by remote operation



Grasping and transferring a raw egg　Grasping and transferring a potato chip　Grasping and transferring a card



Haptic information was presented by AR even when there was a shield when the robot grasped an alcohol container.

(d) Verification of delicate operations using the visual haptics technique

Fig. 5 Remote machine operation technology for a wide dynamic range of manipulation from high power to delicate manipulation[6]

then transmit the data to remote locations. This can mitigate the physical and mental stress for people, helping them to expand their mind and body. We expect these technologies will enable remote work that increases safety and security for people and living with family members and friends in familiar areas, and will also contribute to realizing a harmonious world where people and machines can work together anytime and anywhere (Fig. 6).

6. Acknowledgements

We thank Shimizu, manager at MEE, and Michita, Ueda, Kimura, and Tomita at MEE for producing the H/W, Kanda and Sato at MMS for producing the S/W, and

Fig. 6 A world where people and machines can live in harmony
"A harmonious world where people and machines can work together anytime and anywhere"

Katsumata, Saruta, and Hoshino at Mitsubishi Electric Corporation for the integration (titles omitted).

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Cooperative AI for Human–Machine Work

Authors: *Saori Matsunaga*, Toshisada Mariyama*, Takuji Morimoto**, Yoshihiro Mitsuka** and *Takumi Sato**

1. Introduction

In the "new normal" society with the need to save labor and increase the separation among workers, humans and machines may more often coexist. Currently, the workspace of humans is usually separated from that of machines to ensure safety. To improve efficiency, however, humans and machines will need to work together in the future. Accordingly, Mitsubishi Electric Corporation has developed, using its AI technology Maisart, cooperative AI for human–machine work that makes it easier for machines to work together with humans by imitating the natural behavior of humans. The technology uses inverse reinforcement learning to attain efficient learning with small data sets. This paper introduces the cooperative AI for human–machine work using the example of applying the technology to a small autonomous mobile system.

2. Outline of the Technology

2.1 Overview

Figure 1 illustrates an overview of the proposed technology. The manipulation data of cooperative actions performed by a human is imitated through inverse reinforcement learning (2.2), which realizes natural cooperative actions. Because the process of trial and error needs to be repeated in this approach, a simulation environment that mimics the actual environment needs to be prepared. The sensor data output from the simulator and actual machine needs to be appropriately processed in advance to convert it to an easy-to-learn format. In addition, to control actual machines, a control cycle and method that are suitable for each machine need to be adopted. Generally, autonomous mobile systems require movement control in a cycle of several milliseconds. However, when determining routes approximately, control in cycles of 100 to several hundred milliseconds is sufficient. For these reasons, functions are divided into several modules: a top-down view generator and feature extraction network that pre-process the input data; a learner and trained model that determine approximate target actions; and a control module that performs fine control. This makes it possible to perform both high-speed smooth control and make difficult judgments in actual environments. Each module is explained below.

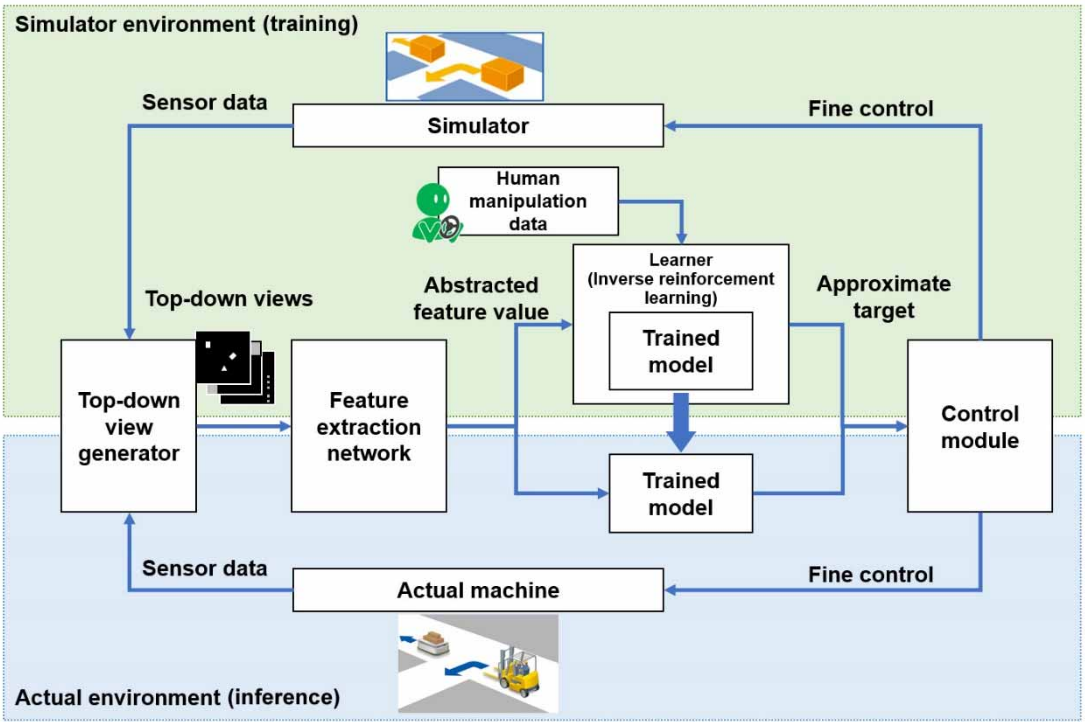

Fig. 1 Overview of the proposed framework

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2.2 Learner (inverse reinforcement learning)

When multiple persons (or machines that humans operate) work in the same environment, operators see the movements of other operators or machines and adjust the speed and sequence of their own operations, ensuring the safety of all operators as well as efficiency. Therefore, in an environment where humans coexist with automated guided vehicles (AGVs) and other machines, the machines should give way to humans or move slowly. Currently, however, because machines move based on predetermined rules such as "advance" and "stop when detecting an obstacle," the operation efficiency of both sides may decrease, for example, when both the machine and operator cannot move. One possible solution would be to give desired action rules for possible events, but it is difficult to list up all rules. Accordingly, we used AI to make machines cooperate with humans. One approach using AI is reinforcement learning for which it is necessary to design a function called a reward function that indicates whether the response to a status is good or bad. However, in autonomous mobile system control in which the surrounding environment changes in a complex manner, it is difficult to design such reward functions. Another technique is called imitation learning, in which behavior is learned such that it becomes similar to a sample action and for which no reward function is designed. There are multiple methods of imitation learning. One method, which uses sample data (demonstration data) to learn behavior in supervised learning, requires a large volume of demonstration data. This is because for statuses that are not included in the training data, appropriate behavior cannot be determined and so errors that may occur during the control need to also be considered and data sets that include these errors need to be prepared. Another method is inverse reinforcement learning. In this method, based on demonstration data, machines estimate reward functions by repeating trial and error through simulation and then use the estimated reward functions to perform reinforcement learning. Generative adversarial imitation learning (GAIL)(1), which is one type of inverse reinforcement learning, learns the optimum behavior in accordance with the procedure of generative adversarial networks (GANs).(2) It has been reported that this method requires fewer demonstration data sets for learning than supervised learning. For this reason, our technology uses GAIL.

2.3 Top-down view generator and feature extraction network

Mobile system control using AI often involves image input. One reason is that images can easily show the positional relationships between multiple objects in an environment where the statuses of a target car and surrounding objects constantly change. However, the obtained images usually contain information that is unrelated to deciding the behavior of the target car. In addition, if a simulator is used for learning, differences between images used in the learning and actual images in actual control cause problems. Therefore, a top-down view generator is used to convert information obtained by the simulator and actual machine into virtual images. This reduces differences between the actual environment and simulation environment while cutting unnecessary information. At present, top-down views are used to simply express the positional relationships between the target car and surrounding objects. Although information on the surroundings can be obtained by top-down views, the number of dimensions of image data is large, which may adversely affect the speed and stability of learning. To solve this problem, a feature extraction network is introduced to compress the obtained top-down views to extract lower-dimensional feature values. In our technology, a variational autoencoder (VAE) is used to convert views into lower-dimensional vectors. By creating a large quantity of various types of artificial top-down views, feature extraction network learning can be completed before inverse reinforcement learning. The final input data is a combination of the feature values extracted from top-down views with information on the speed and other factors that is not included in the top-down views.

3. Application to a Small Mobile System

3.1 Scenarios

We applied this technology to a small autonomous mobile system imitating an AGV in an experiment; the results are shown below. Figure 2 shows the experimental scenario. The target AGV travels in a straight line to the right along the thick solid line in the figure. It aims to reach the right end as fast as possible without colliding with or hindering the forklift. The forklift retreats so as to cross the travel route of the AGV, changes direction, and then travels to the right as shown by the broken lines in the figure. Therefore, if the AGV travels according to the rules of "advance" and "stop when detecting an obstacle," it will collide with the forklift or both the AGV and forklift will stop in front of each other depending on the timing when the forklift retreats (Fig. 3). In this experiment, two patterns were provided as the timing when the forklift edges into the travel route of the AGV: (a) a sudden interrupt that forces the AGV to retreat and (b) a slow interrupt that does not require the AGV to retreat. The two scenarios were mixed for learning and evaluation. The time at which the AGV and forklift started and their start positions were slightly changed every time.

3.2 Learning using a simulator

We used a simulator that we had developed in the

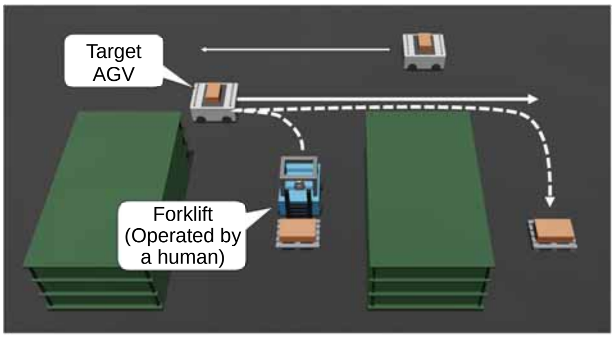


Fig. 2 Experimental scenario

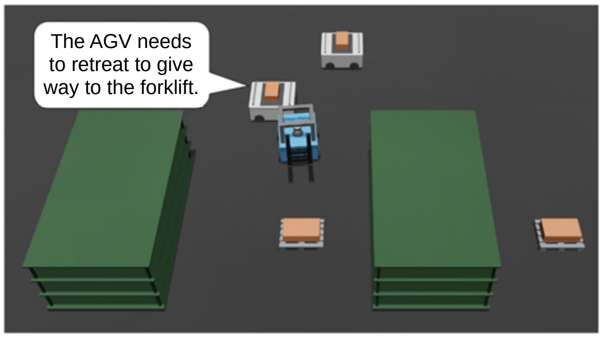
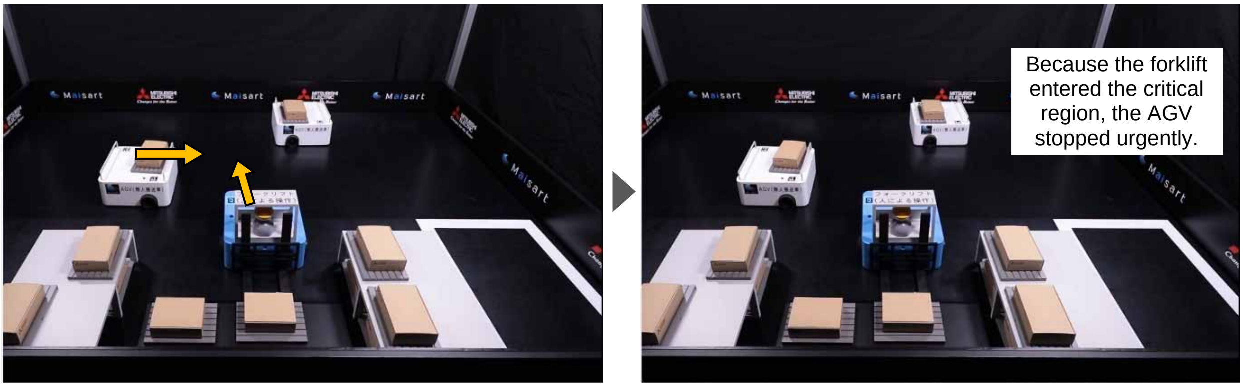
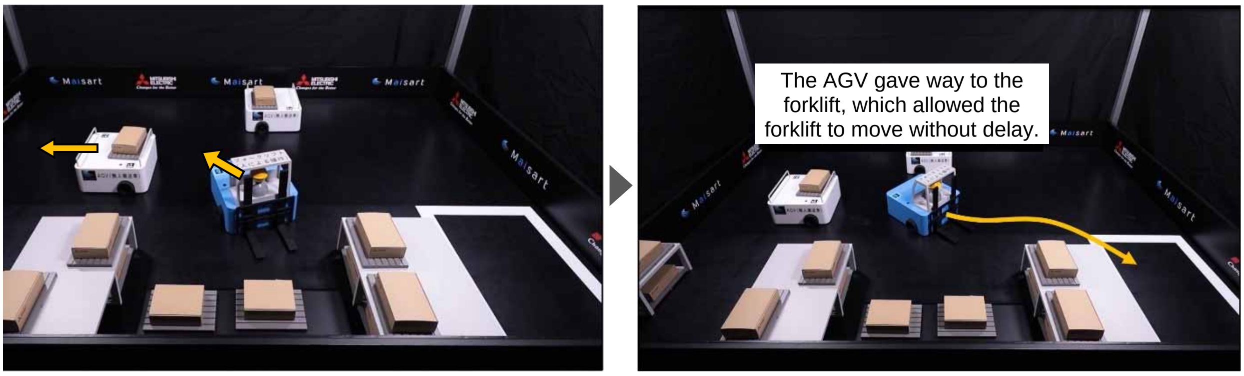


Fig. 3 An example of a scene that requires cooperative motion



(a) The cooperative AI for human–machine work was not applied.



(b) The cooperative AI for human–machine work was applied.

Fig. 4 Real-world experiments with cooperative AI

learning of cooperative actions for the scenarios described in the previous section. The target of a top-down view is a square area of side 1 m with the target car at the center; binary images with only another vehicle included were used. The feature extraction network was used to convert a top-down view to 16-dimensional vectors and the speed of the target car was added to them. Therefore, the input data has a total of 17-dimensional vectors. Demonstration data was collected when a human operated the AGV on the simulator for each of scenarios (a) and (b). Inverse reinforcement learning and supervised learning were performed and the scores were calculated based on whether the AGV collided with the forklift and the time required to complete the operation and compared. As a result, although limited to the scenarios used this time, when four or more demonstration data sets were available for each of scenarios (a) and (b) in the inverse reinforcement learning, the obtained scores were the same or higher than those of humans. On the other hand, in the supervised learning, even when the number of demonstration data sets used was ten or more times those used in the inverse reinforcement learning, the scores of the supervised learning were lower than those obtained in the inverse reinforcement learning and they also widely varied. These results confirm that our proposed technology is superior to supervised learning for the number of required data sets, as well as safety, efficiency, and stability of operations.

3.3 Experiment using actual machines

Lastly, the results of an experiment using actual machines are shown below. As shown in Fig. 4, in the experiment, the AGV, forklift, and surrounding objects used are the same as those in the simulation environment shown in Fig. 2. A model trained with 20 demonstration data sets was applied to the target AGV without additional learning and adjustment. When the AGV moved according to the rules of “advance” and “stop when detecting an obstacle,” at the moment when the forklift entered its critical region, the AGV stopped urgently, which resulted in operation time loss (Fig. 4(a)). On the other hand, when our technology was applied, the AGV retreated to give way to the forklift, which allowed the forklift to travel without delay. These results show that our technology contributes to realizing smooth operations (Fig. 4(b)).

4. Conclusion

When the cooperative AI for human–machine work was used, natural behavior was obtained with fewer demonstration data sets thanks to the inverse reinforcement learning. In addition, combining the cooperative AI with a top-down view generator and feature extraction network realized cooperative actions of the actual machine. We will keep working on development toward applying the technology to actual production and distribution sites where humans and machines may coexist and to autonomous driving.

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Technologies for Improving Hygiene in Air Conditioners

Authors: *Akane Nakanishi**, *Reiji Morioka*** and *Koji Ota**

1. Introduction

There is increasing demand for better hygiene on the inside of products, in addition to better indoor air quality (IAQ) and indoor environmental quality (IEQ). Mitsubishi Electric Corporation has developed technologies for improving the hygiene of air conditioners that prevent substances whose safety has not been verified from being released to environments where humans are present, considering the potential impact on the human body. This paper introduces these technologies.

2. Hygiene Improvement Technology 1: Electrostatic Mist Treatment Technology

Mitsubishi Electric has developed an electrostatic mist treatment technology to sterilize and inactivate airborne microbes in indoor spaces to improve IAQ. Figure 1 illustrates the electrostatic mist generation structure and airborne microbial activity suppression mechanism, a Peltier cooler is used to condense moisture in the air into water on the cooling plate. The condensed water drips onto a hygroscopic high-voltage electrode. A high voltage is applied and the electrostatic atomization mechanism forms fine water droplets and releases them into the air. Porous formed titanium is used as the hygroscopic high-voltage electrode, enabling a large quantity of fine water droplets to form and improving the corrosion resistance. In addition, pure fine electrostatic water droplets with particle diameters of 10–40 nm are formed by controlling the applied voltage. Such water droplets do not contain ozone gas and radicals, which have high oxidizing power. Electrostatic mist absorbs airborne microbes by the charging effect and thereby suppresses their activity in the air. The mist does not affect the human body because it does not contain ozone gas or radicals.

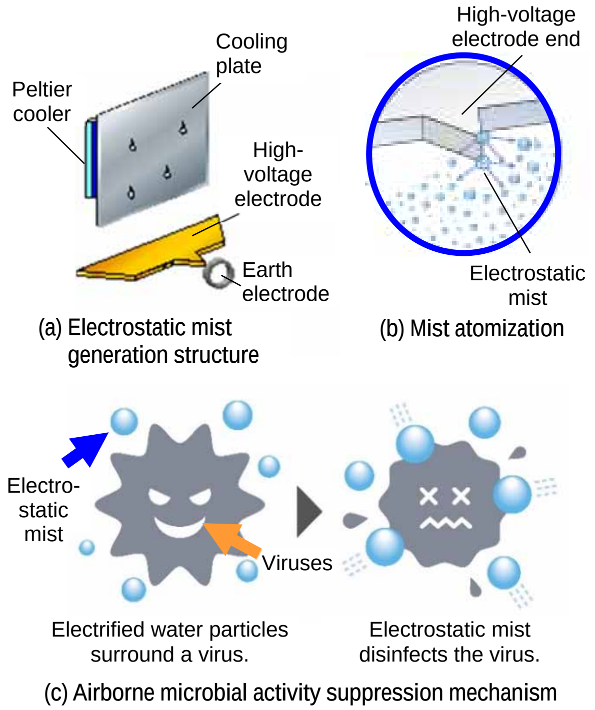

Fig. 1 Electrostatic mist generation method and airborne microbial activity suppression mechanism

The inactivation effect of the electrostatic mist treatment against airborne influenza viruses (influenza A virus: A/Aichi2/68(H3N2)) was verified. It was found that there were fewer airborne viruses when electrostatic mist was released than in the case of natural decrease when no mist was released, and the number decreased by two orders of magnitude (99%) in 158 minutes. These results show that electrostatic mist can disinfect airborne viruses.

Mitsubishi Electric's room air conditioners that utilize this technology come under the name of "PURE MIST."

3. Hygiene Improvement Technology 2: Wet ozone Treatment Technology

The inside of air conditioners during air-cooling is humid and so mold tends to grow. Microorganism-based volatile organic compounds, which are created when mold propagates, cause offensive odors and also mold spores may cause allergies.(1) Therefore, there is a need for technologies to kill and prevent mold inside air conditioners. Because mold spores are protected by coating layers and cell walls composed of protein, the concentration-time value (CT) (ozone gas concentration (ppm) × exposure time (min)) necessary to kill 99% of mold by ozone treatment is large: approximately 5,400 ppm•min.(2) Therefore, it takes a long time to kill mold by ozone treatment with ozone gas at a concentration equal to or lower than the environmental standard value (0.05 ppm). Mitsubishi Electric, focusing on the fact that spores germinate under high humidity and that the coating layers and cell walls cleave, has developed a wet ozone treatment technology for treating ozone gas at high humidity.

Figure 2 shows the fungicidal effect against spores of *Aspergillus niger* NBRC 6341 applied to the inside of

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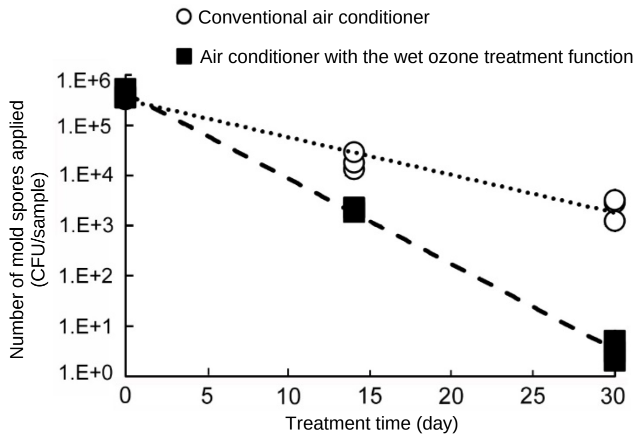
an air conditioner with the wet ozone treatment function. The number of mold spores on the air conditioner with this treatment function is less than that on a conventional air conditioner without the function: 99% or more of mold can be killed through exposure to wet ozone gas in 30 days (as in Figure 2, the CT is 30 ppm•min). These results show that the wet ozone treatment efficiently kills mold.

Mitsubishi Electric's room air conditioners feature this inside cleaning technology under the name of "FUNGICIDAL CLEAN SHOWER."

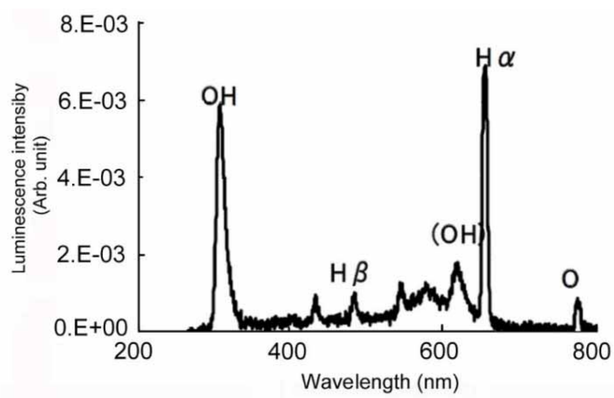
4. Hygiene Improvement Technology 3: Technology for Pulsed High-Voltage Discharge Treatment in Water

During cooling operation of air conditioners, water condenses on the heat exchangers in the indoor units. In packaged air conditioners, this condensed water is stored in drain pans and then discharged by pumps. If microorganisms breed in the stored water, the resulting offensive odors may be released or the air conditioner may malfunction due to the formation of biofilm. To prevent these problems, Mitsubishi Electric has developed a technology for pulsed high-voltage discharge treatment in water. For this technology, a discharge electrode and a rod-shape metal earth electrode are placed in water. The discharge electrode is a small-diameter metal wire whose circumference has been molded with resin. A pulsed high voltage is applied to the section between these electrodes, causing the formation of hydroxy radicals (OH•; "•" indicates an unpaired electron), hydrogen radicals (H•), and other radicals as shown in Fig. 3 in the water. These radicals oxidize and break the cell walls and cell membranes of



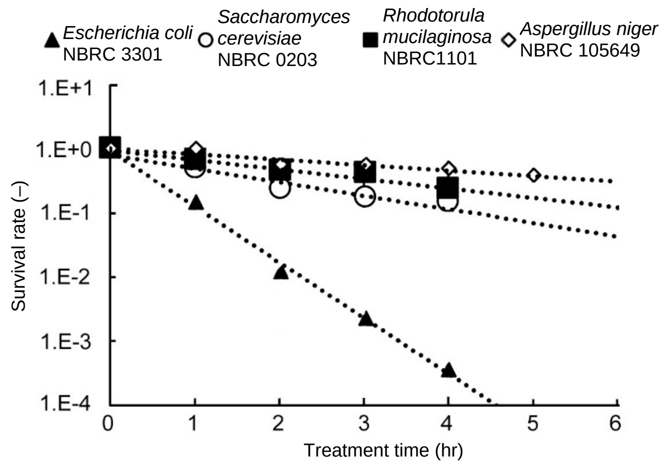
Conventional air conditioner operation:	A cycle of 6-hour cooling operation and 6-hour stopped was repeated.
Wet ozone treatment (twice/day):	When no cooling operation is performed, 10-minute ozone gas treatment (maximum ozone gas concentration in the air conditioner: 0.05 ppm) was performed.
Test period:	30 days, 5.5×10^{6} CFU of mold spores applied

Fig. 2 Fungicidal effect of wet ozone treatment



Discharge conditions: Applied voltage:	−8kV, pulse frequency: 130 Hz, discharge electrode wire diameter: 0.3 mm, earth electrode wire diameter: 1 mm
Test water:	Water imitating the components of actual drain water (imitation drain water: total organic carbon TOC: 40 mg/L, electrical conductivity: 130 μS/cm)
Measuring instrument:	Discharge light spectrum analyzer (CSP-TSP-100MDN)

Fig. 3 Spectral characteristics using pulsed high-voltage discharge in water



Discharge conditions: Applied voltage: −4 kV, pulse frequency: 130 Hz, discharge electrode wire diameter: 0.3 mm, earth electrode wire diameter: 1 mm

Test water: Imitation drain water, water quantity: 50 mL

Fig. 4 Bactericidal effect of pulsed high-voltage discharge in water

microorganisms, thus inactivating them and achieving disinfection.

Figure 4 shows the bactericidal effect of the pulsed high-voltage discharge treatment in water against various types of microorganisms (bacteria, yeasts, and mold spores). The longer the treatment time, the lower the survival rates of all the microorganisms. The technology can kill *Escherichia coli*, which are prokaryotes (living things without a cell nucleus) under water, and also yeasts and molds (eukaryotes), demonstrating bactericidal effects. These results show that pulsed high-voltage discharge treatment in water can suppress the formation of biofilms, which are aggregates of multiple microorganisms. Mitsubishi Electric's packaged air conditioners feature this drain pan cleaning technology under the name of "PULSE CLEAN."

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Thermal Diode IR Sensor Technology

Author: *Daisuke Fujisawa**

1. Introduction

Uncooled infrared (IR) image sensors are typical sensors that combine Si-LSI and micromachining technologies. In recent years, the performance of these sensors has steadily improved thanks to advances in micromachining technologies. There are several types of uncooled IR image sensors. Mitsubishi Electric Corporation has proposed and developed the thermal diode type in which monocrystalline Si diodes formed on Silicon On Insulator (SOI) layers are used as thermal sensors.[(1)(2)(3)(4)(5)(6)] This type, for which diodes made from Si monocrystals are used at the thermal sensor sections, is characterized by excellent uniformity of sensitivity in the screens of image sensors. There are demands for uncooled IR image sensors with smaller pixel size to reduce cost, and more pixels to increase image resolution. Technologies to satisfy such needs have been developed. This paper describes a technology for thermal diode IR sensors, which is an expanding market (e.g., consumer goods).

2. Thermal Diode IR Sensors

2.1 Thermal diodes

Figure 1 shows a cross section of the pixel structure of a thermal diode IR sensor. In the well heat-insulated thermal sensor section, the thermal diodes are retained with support legs over cavities formed in the substrate. Based on the dose of incident infrared radiation, the temperature of the thermal diodes changes. A forward bias constant current is supplied to the diodes from the outside and the dose of incident infrared radiation is read as the change in forward voltage caused by the change in diode temperature. This uses the characteristic of thermal diodes (thermal sensors) that when their temperature increases due to incident infrared radiation, the forward voltage (V_f) decreases with a constant current behavior. In addition, the sensitivity of a thermal diode IR image sensor to the temperature of a subject is proportional to the temperature change coefficient (dV_f/dT) of the forward voltage (V_f) of the thermal diodes. Because this coefficient depends on the number of diodes connected in series, increasing the number of diodes connected in series within the drive (power source) voltage enhances the sensitivity of the sensor.

2.2 Chip-scale packaging

For an uncooled IR image sensor, pixels (thermal sensors) with a thermal insulation structure are formed on a silicon substrate and so the thermal diodes (thermal sensors) need to be kept under vacuum. Conventionally, the entire sensor was vacuum-sealed using a ceramic package or other part. However, this method increases the cost and size. Mitsubishi Electric has therefore developed a chip-scale packaging technology. In this method, as shown in Fig. 2, a seal frame is formed to surround the pixel area, a window part that lets infrared radiation through is bonded, and only the pixel area is sealed under vacuum. The chip-scale packaging technology eliminates the need for conventional ceramic packages, greatly reducing the sensor size.

2.3 Measurement of subject temperature

The output of a thermal diode IR sensor is a function of the emissivity of a subject, subject temperature, sensor temperature, and sensor module temperature.

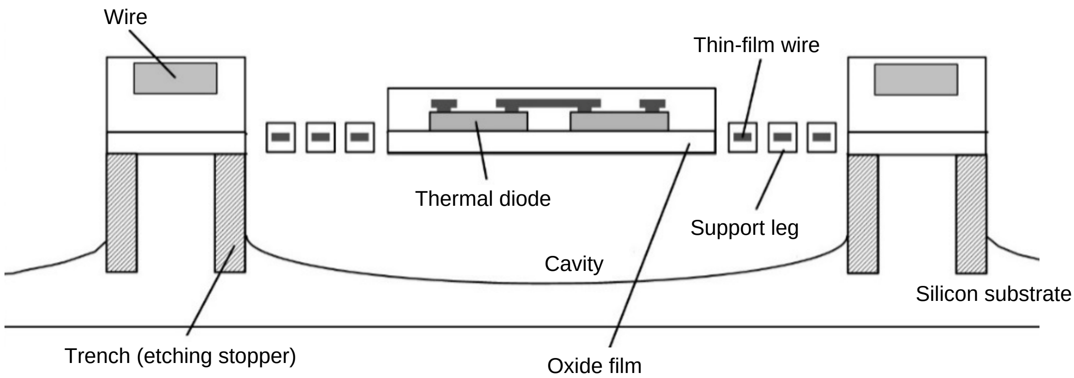

Fig. 1 Pixel structure of thermal diode IR sensor

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Therefore, the output of a thermal diode IR sensor changes depending on the offset of each pixel output, its sensitivity to radiation, and temperature characteristics. Accordingly, the shutter needs to be closed at certain intervals to enable the sensor to see a subject (shutter) of uniform temperature in order to correct the characteristics of each pixel. Figure 3 shows an example of the environmental temperature dependence of sensor output on subject temperature.

In our thermal diode method, monocrystalline Si diodes are used and so, in the temperature range of normal sensor environments, the relationship is almost linear. Therefore, even when two-point signal correction based on data under two environmental temperature conditions (20°C, 40°C) is applied, FPN is 0.1°C or lower, which provides sufficient performance for temperature analysis in units of 0.1°C. The value of FPN is obtained by converting the standard deviation of each pixel output of a thermal diode IR image sensor when a subject of uniform temperature is pictured into the subject temperature. A smaller value of FPN is better.

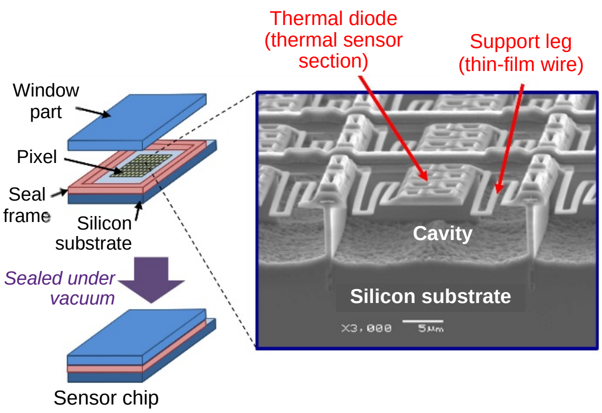

Fig. 2 Chip-scale vacuum package

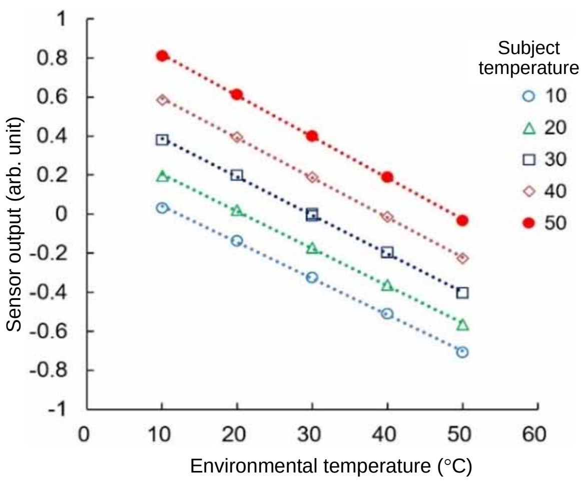

Fig. 3 Environmental temperature dependence of sensor

3. Development of Higher-Performance IR Sensors

3.1 Technology for downsizing thermal diodes

The downsizing of each pixel in 2-dimensional pixel arrays of thermal diode IR sensors reduces the sensor chip size, which can reduce the cost and also the size of sensor modules including the optical systems. Consequently, downsizing of pixels is an important trend in the development of uncooled IR sensors. For example, if the pixel pitch is reduced from 25 μm to 17 μm, the pixel area is reduced by half, greatly reducing the area of the thermal sensor section. Therefore, to maintain the sensitivity, some measures are required: (1) higher sensitivity of thermal sensors and (2) higher heat insulation of support legs. The thermal diode method has a characteristic that the greater the number of diodes connected in series, the higher the sensitivity. Therefore, it is important to reduce the area of a single diode. In the conventional structure, PN diodes are connected in series by dividing them with isolation regions of oxide films. Mitsubishi Electric has developed a 2-in-1 diode structure in which a PN diode and NP diode are paired and connected without an isolation region. This structure can reduce the area of diodes by over 15%.

3.2 High-sensitivity readout circuit technology

It is also important to improve the sensitivity of thermal diode IR sensors to enhance the accuracy of measurement of subject temperature. As described above, one way to enhance the sensitivity is to increase the number of diodes connected in series at a thermal sensor section, but this requires a higher source voltage. If there is a limitation on the source voltage, the higher-sensitivity readout circuit shown in Fig. 4 can be used to increase the sensitivity without changing the number of diodes connected in series.

As the diode temperature increases (decreases), the forward voltage (V_f) decreases (increases). The gate voltage at Md, which is obtained by subtracting V_f from the source voltage, increases (decreases) and the current at Md decreases. This decrease (increase) in the current reduces (increases) the diode current (I_f) by the current mirror circuit. This further reduces (increases) the diode forward voltage. Therefore, because the circuit configuration illustrated in Fig. 4 has a positive feedback loop for the change in diode forward voltage (V_f) and the change in diode current (I_f), the obtained change in output voltage is more than the change in pixel output voltage obtained by a single diode, which increases the sensitivity for a single diode. Figure 5 shows the output characteristics of a sensor using this higher-sensitivity readout circuit.

As a result of using the higher-sensitivity readout circuit, the diode temperature change coefficient (dV_f/dT)

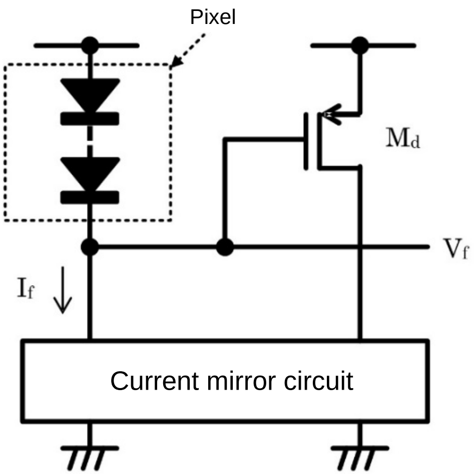

Fig. 4 Circuit diagram

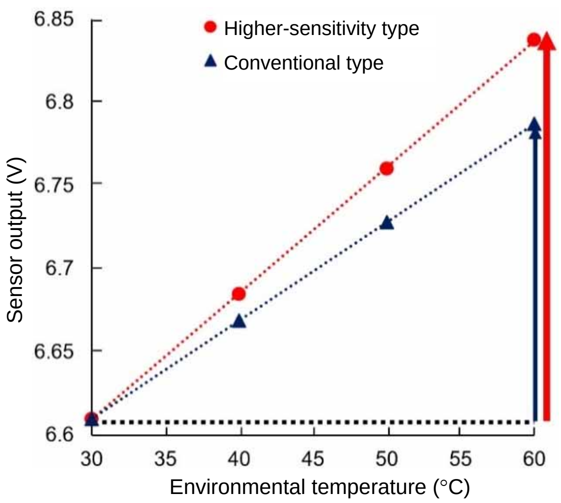

Fig. 5 Temperature dependence of output (V_f)

is 1.9 mV/K (per piece), which is approximately 1.3 times (per piece) that of the conventional readout circuit. When circuits in this configuration are arrayed, a positive loop circuit, current source, and integration circuit are provided for each row of the array of multiple pixels.

4. Conclusion

This paper introduced the thermal diode IR sensor technology. For thermal diode IR sensors, the thermal sensors can be manufactured by Si-LSI technology and so the method is suitable for cost reduction and mass production. These sensors can be applied to various purposes, such as crime prevention, monitoring, air conditioning, lighting, equipment control, counting numbers of people, and measurement and monitoring of body temperature. Low-priced IR sensors are expected to become increasingly important in the consumer goods sector and thermal diode IR sensors are likely to be key devices for developing new IR sensor applications.

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